Planning Observations, Data Access, and Software Tools

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The CHARA Array of
Georgia State University

Mount Wilson, CA

With contributions from:
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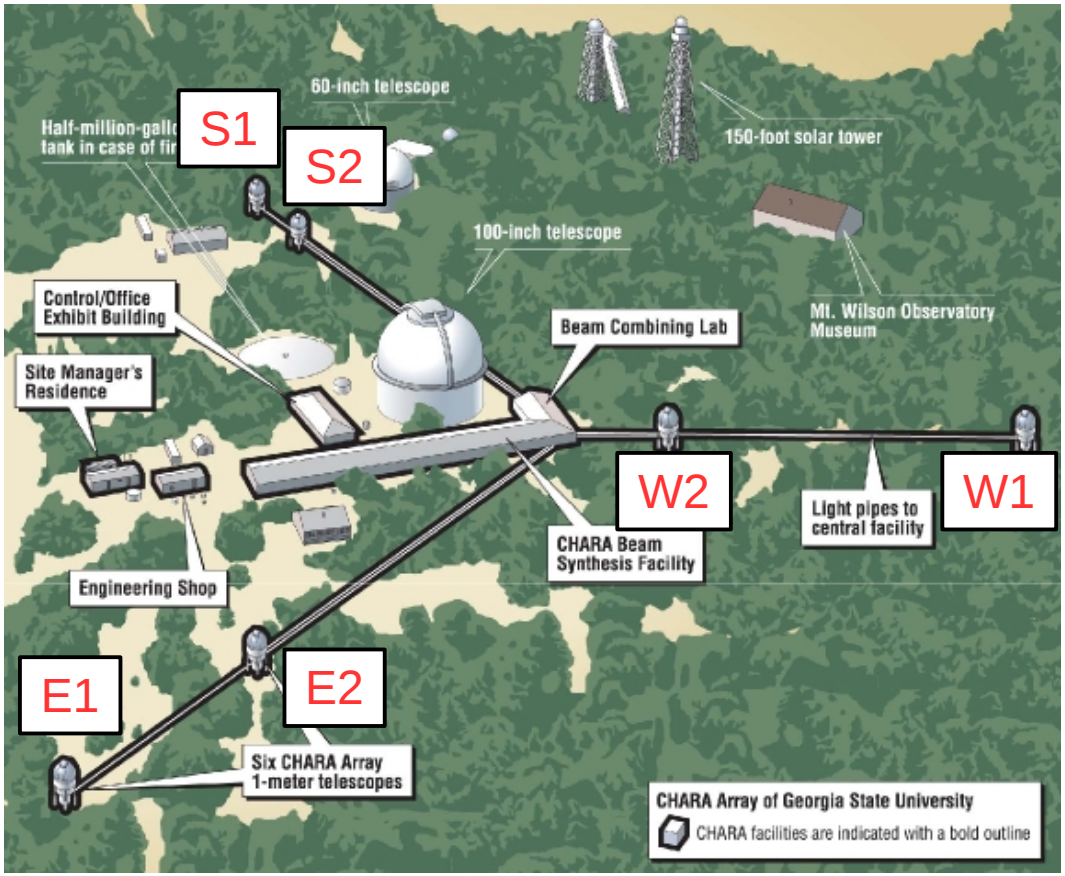
Christopher Farrington, and Jeremy Jones

Beam Combiners

Combiner	Num Tel.	Band	Typical Mag	Best Mag	Spec. Res.	Science
CLASSIC	2T	H or K	7.0	8.5	Broad	Diameters
CLIMB	3T	H or K	6.0	7.0	Broad	Binaries, disks
JouFlu	2T	K	4.5	5.0	Broad	Diam, precision
MIRC	6T	H	5.0	6.0	40	Stellar imaging, binaries, disks
PAVO	2T	630-900 nm	7.0	8.0	30	Diameters
VEGA – HiRes	2-4T	2 bands (7nm) in 480-850 nm	4.0	5.0	30000	Spectral studies
VEGA – MedR	2-4T	2 bands (35 nm) in 480-850 nm	6.5	7.5	6000	Spectral studies, diam.

Limit for acquisition and tiptilt tracking: V = 10-12 mag

Telescopes and Baselines

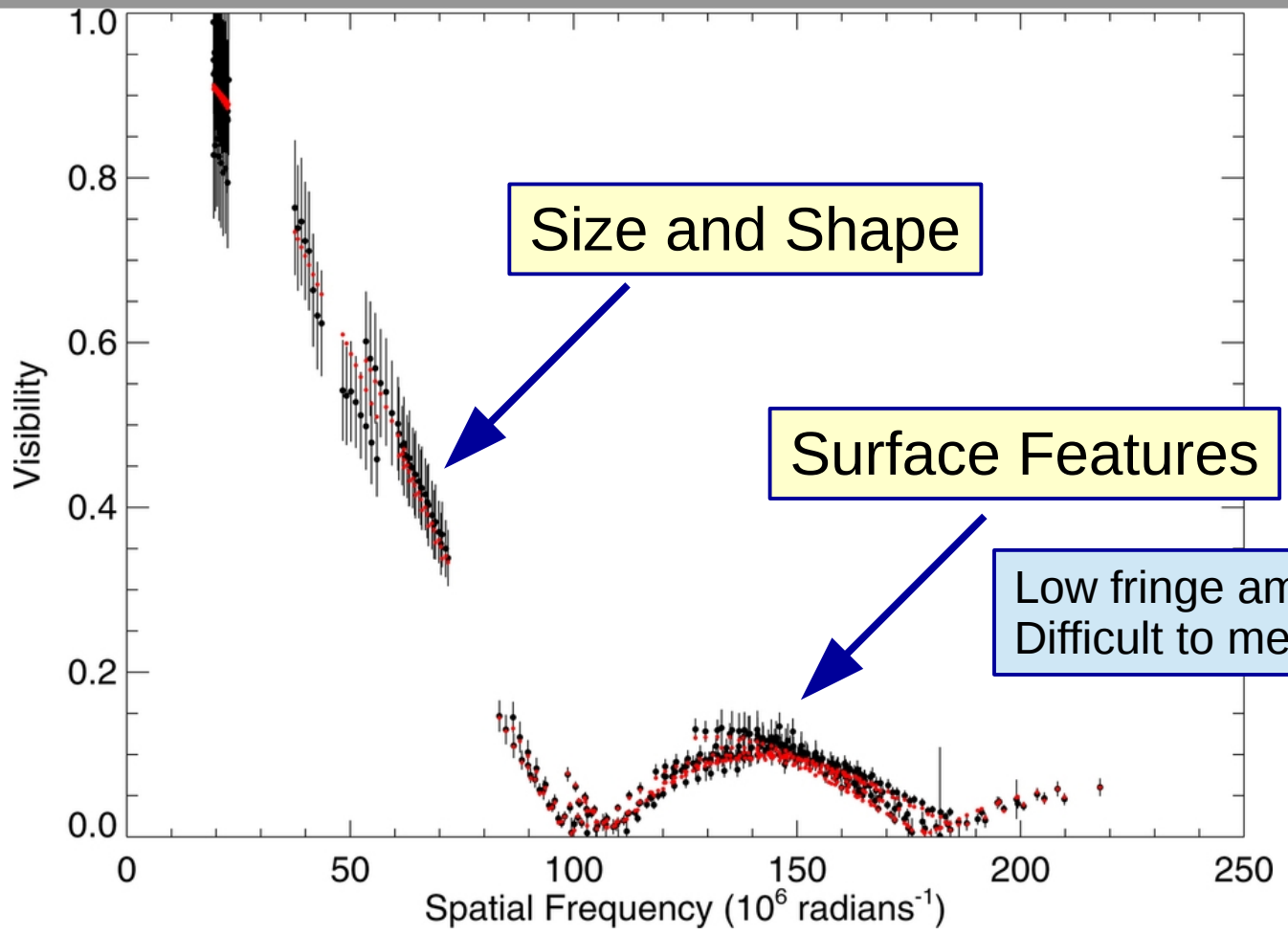


Baseline	Length (m)
E1-S1	331
W1-E1	314
E1-S2	302
E2-S1	279
W1-S1	279
W1-E2	251
W1-S2	249
E2-S2	248
W2-S1	211
W2-E1	222
W2-S2	177
W2-E2	156
W2-W1	108
E2-E1	66
S2-S1	34

Selecting Baseline Length

- Angular Resolution on Longest Baseline: 0.5 λ /B
  - 0.66 mas in K-band (2.13 μm)
  - 0.52 mas in H-band (1.67 μm)
  - 0.20 mas in visible at 650 nm
- Resolving stellar diameters
  - Select baseline that can resolve target star
- Imaging stellar surface features
  - Sample beyond the first null (at 1.22 λ/B)

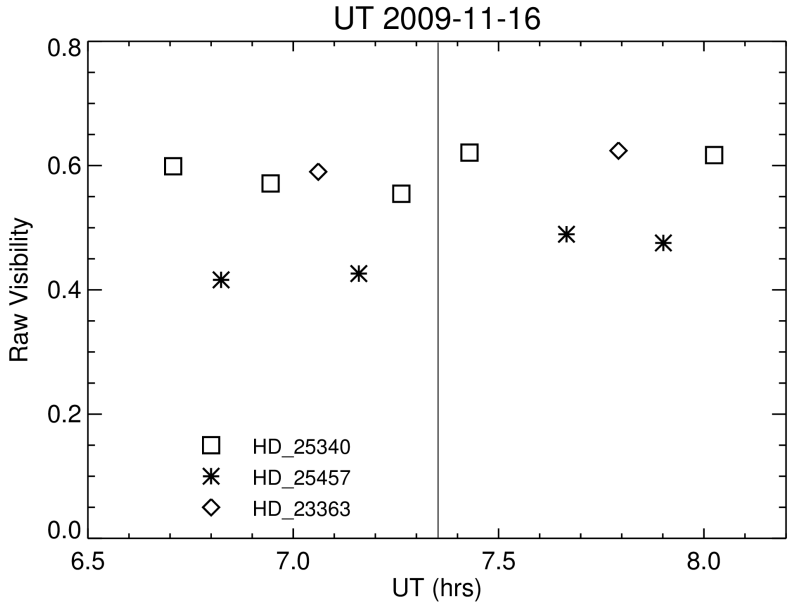
Selecting Beam Combiner and Baselines



How Many Telescopes?

- Stellar diameter:
  - One or two baselines
- Binaries
  - Three or more telescopes
  - (perpendicular baselines, closure phase)
- Imaging stellar surfaces, circumstellar disks
  - Multiple baseline projections (all 6 telescopes)

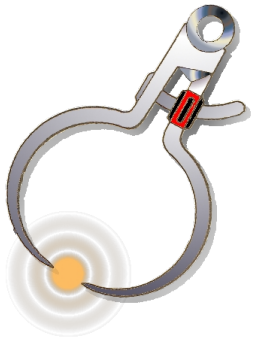
Calibrator Stars



- Instrumental and atmospheric effects will cause a loss in coherence, causing a drop in the measured visibility.
- Observe unresolved calibrator stars to define the true visibility of the target.
  - Within 5-10 degrees on sky
  - Within 1-2 mag in brightness

Selecting Calibrators: SearchCal

JMMC



www.jmmc.fr/searchcal_page.htm

SearchCal [c1]

File Edit Query Calibrators Interop Help

Query Parameters

1) Instrumental Configuration
Magnitude Band : H
Wavelength (H) [µm] : 1.65
Max. Baseline [m] : 300.0

2) Science Object
Name : HD 69897
RA 2000 [hh:mm:ss] : 08 20 03.86158
DEC 2000 [+/-dd:mm:ss] : +27 13 03.7416
Magnitude (H) : 3.942

3) SearchCal Parameters
Min. Magnitude (H) : 3.0
Max. Magnitude (H) : 5.0
Scenario : Bright Faint
RA Range [mn] : 240.0
DEC Range [deg] : 20.0

Progress : Get Calibrators

Found Calibrators (2041 sources, 1826 filtered)

Index	dist	HD	RAJ2000	DEJ2000	vis2	LDD	UD_V	UD_H	UD_K	SpType	V	H	K
1	5.21E-6	69897	08 20 03.8602	+27 13 03.7380	0.374	0.701	0.662	0.686	0.689	F6V	5.13	3.942	3.868
2	2.975	67542	08 09 35.1816	+29 05 35.0772	0.622	0.503	0.468	0.488	0.49	G0II	6.47	4.699	4.621
3	3.383	67544	08 09 24.8645	+24 49 34.0716	0.619	0.509	0.468	0.49	0.493	G8III	7.29	4.966	4.908
4	3.595	71730	08 29 40.0634	+24 20 40.9452	0.581	0.542	0.496	0.52	0.523	K0III	7.05	4.872	4.81
5	3.977	73080	08 37 22.1112	+28 17 39.8328	0.554	0.555	0.52	0.541	0.543	G5	6.63	4.702	4.591
6	4.945		08 10 54.7320	+22 43 43.1904	0.514	0.588	0.548	0.573	0.575	K0	8.026	4.909	4.698
7	6.121	65471	07 59 42.6055	+23 10 58.4652	0.506	0.594	0.554	0.579	0.581	K0	6.92	4.73	4.562
8	6.902	75216	08 49 45.3118	+29 26 55.9824	0.534	0.581	0.529	0.557	0.561	K2III	7.38	4.868	4.712
9	7.14	63138	07 48 28.8108	+28 45 51.2748	0.519	0.592	0.542	0.568	0.572	K0III	6.86	4.694	4.605
10	7.303	75646	08 52 00.4543	+25 43 07.1004	0.568	0.553	0.504	0.53	0.534	K2III	7.54	4.983	4.834
11	7.524		08 52 09.6634	+29 51 13.3848	0.515	0.588	0.548	0.572	0.575	K0	7.08	4.742	4.631
12	7.677		08 32 54.2333	+34 23 03.2748	0.544	0.565	0.524	0.549	0.552	K2	7.52	4.934	4.798
13	7.731	75783	08 53 00.0972	+29 57 41.5296	0.564	0.549	0.509	0.533	0.536	K2	7.35	4.982	4.813
14	7.809	74198	08 43 17.1466	+21 28 06.6000	0.774	0.366	0.351	0.362	0.362	A1IV	4.66	4.788	4.638
15	7.842	64092	07 53 01.0094	+22 20 04.3116	0.557	0.553	0.515	0.538	0.541	K0	7.05	4.85	4.755
16	7.845		08 03 34.1340	+20 20 18.6972	0.599	0.519	0.486	0.506	0.508	G5	7.03	4.836	4.742
17	8.769	67482	08 09 39.7601	+35 42 08.5032	0.58	0.535	0.498	0.52	0.523	K0	7.3	4.952	4.839
18	8.815	64602	07 56 01.9399	+34 22 10.4160	0.572	0.541	0.505	0.527	0.53	K0	7.57	4.972	4.827
19	8.917		07 48 06.8957	+32 51 25.0308	0.557	0.552	0.518	0.539	0.541	G5	7.204	4.952	4.548
20	10.159	60204	07 34 31.5922	+28 41 11.6808	0.519	0.583	0.547	0.569	0.571	G5	6.66	4.605	4.498
21	10.402	77694	09 04 51.4817	+24 36 18.5040	0.561	0.559	0.509	0.536	0.539	K2III	7.8	4.982	4.838

Filters

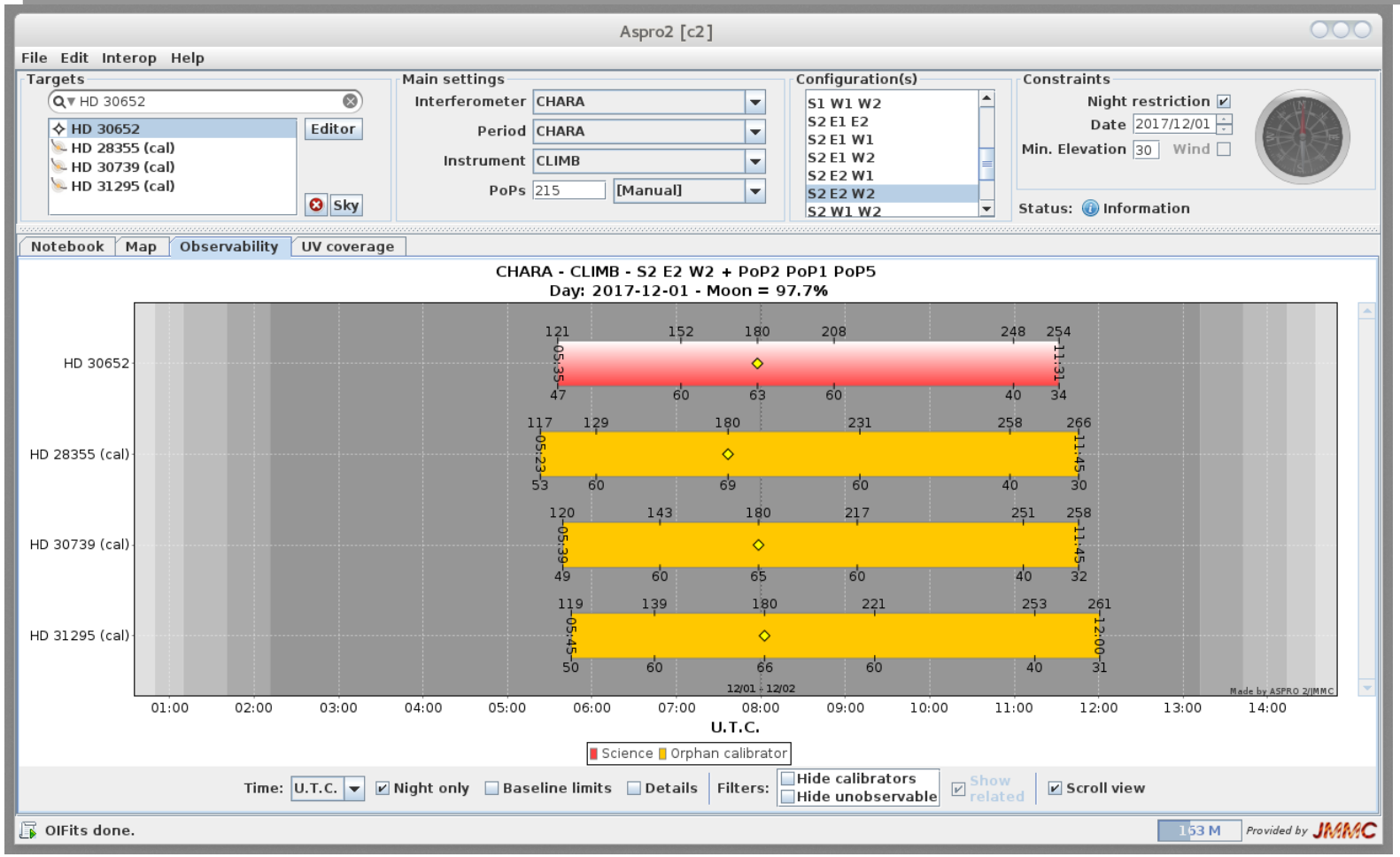
Reject stars farther than : Maximum RA Separation (mn) : 10.0 Maximum DEC Separation (degree) : 10.0
Reject stars with magnitude : below : 0.0 and above : 10.0
Reject Spectral Types (and unknowns) : O B A F G K M
Reject Luminosity Classes (and unknowns) : I II III IV V VI
Reject Visiblity below : vis2 : 0.5
Reject Visibility Accuracy above (or unknown) : vis2Err/vis2 (%) : 2.0
Reject Variability
Reject Multiplicity
Reject Invalid Object Types
Diameter quality : Maximum chi square : 2.0 Maximum relative error (%) : 10.0

searching calibrators... done. 29 M Provided by JMMC

How much time is needed?

- Calibration Strategy:
  - Cal1 – Obj – Cal2 – Cal1 – Obj – Cal2 ...
- Time to collect Cal-Sci-Cal set:
  - Seeing and brightness dependent
  - CLASSIC, CLIMB, PAVO, JouFlu: 15 – 45 minutes
  - VEGA: 30 – 60 minutes
  - MIRC: 90 minutes for Cal-Sci set
- Collect many repeated calibration sets
  - Improve detection, test systematics
  - Increase u,v coverage on the sky

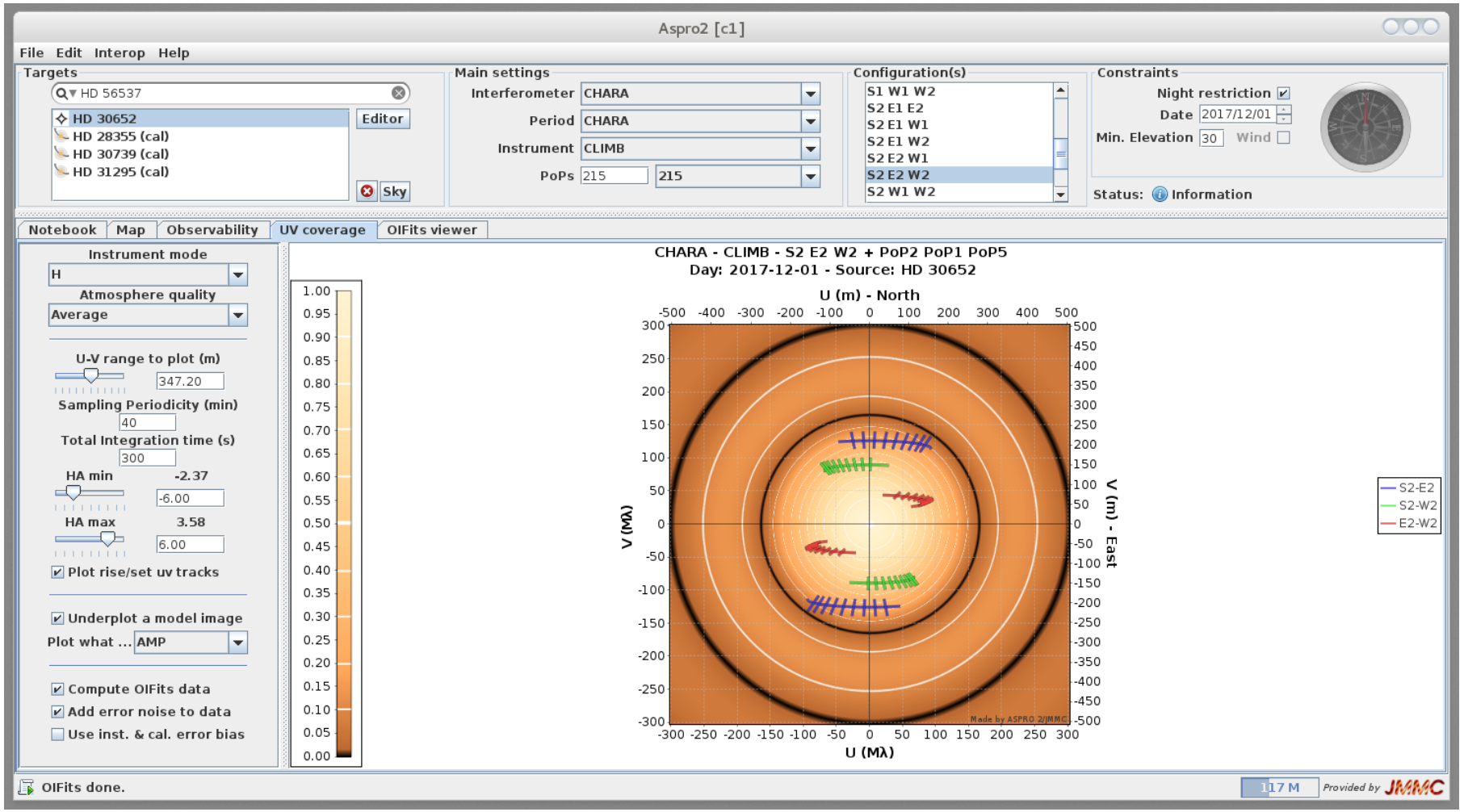
Planning Software: ASPRO 2



http://www.jmmc.fr/aspro_page.htm

ASPRO 2

JMMC


Aspro2 [c1]
File Edit Interop Help
Targets
HD 56537
HD 30652
HD 28355 (cal)
HD 30739 (cal)
HD 31295 (cal)
Editor
Sky
Main settings
Interferometer CHARA
Period CHARA
Instrument CLIMB
PoPs 215
Configuration(s)
S1 W1 W2
S2 E1 E2
S2 E1 W1
S2 E1 W2
S2 E2 W1
S2 E2 W2
S2 W1 W2
Constraints
Night restriction
Date 2017/12/01
Min. Elevation 30
Wind
Status: Information
Notebook Map Observability UV coverage OIFits viewer
Instrument mode
H
Atmosphere quality
Average
U-V range to plot (m)
347.20
Sampling Periodicity (min)
40
Total Integration time (s)
300
HA min -2.37
-6.00
HA max 3.58
6.00
Plot rise/set uv tracks
Underplot a model image
Plot what ... AMP
Compute OIFits data
Add error noise to data
Use inst. & cal. error bias
CHARA - CLIMB - S2 E2 W2 + PoP2 PoP1 PoP5
Day: 2017-12-01 - Source: HD 30652
U (m) - North
V (Mλ)
U (Mλ)
V (m) - East
S2-E2
S2-W2
E2-W2
Made by ASPRO 2/JMMC
OIFits done.
117 M
Provided by JMMC

Community Access Time

- Visitor Support Scientist to help with planning observations
- Observations carried out by CHARA staff
- Visitors are encouraged to travel to the Array to participate in the observations
  - Real-time input from PI on decisions that could impact the science objectives and priorities
- CHARA staff will support data reduction to OIFITS format
  - Data reduction software available for those interested in reducing and calibrating data
- Data analysis, model fitting, image reconstruction performed by users

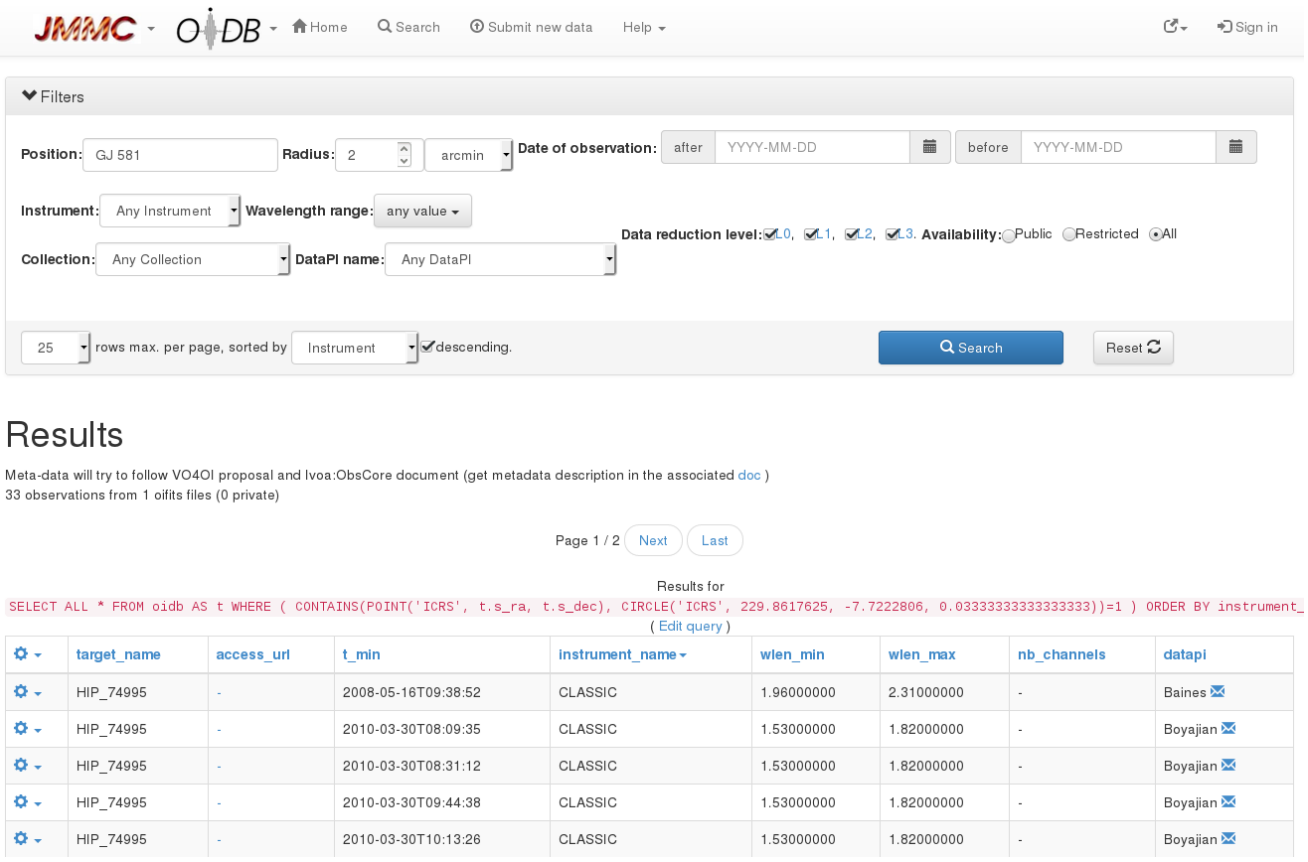
Data Access – The CHARA Server

- Under Development
- Located at GSU Data Center
- 3 Virtual Machines:
  - Database/Archive Machine
  - Data Reduction Machine
  - Remote Observing Machine
    - Active Mode
    - Passive Mode

Data Scientist
Jeremy Jones

Do observations already exist?

- OI Database
- Query and download data (OIFITS)
- CHARA observation logs for VEGA, Classic, CLIMB, (through 2015)
- Logs for all CHARA obs by fall 2018



http://oidb.jmmc.fr

OIFITS Format

- OIFITS: Data exchange standard for Optical Interferometry
- Target and instrument information tables:
  - OI_TARGET
  - OI_ARRAY
  - OI_WAVELENGTH
- Data tables:
  - OI_VIS2
  - OI_T3

OI_VIS2 Table (OIFITS)

TARGET_ID	Target number
TIME	UTC time of observation (s)
MJD	Modified Julian Date
INT_TIME	Integration time (s)
VIS2DATA	Squared Visibility
VIS2ERR	Error in Squared Visibility
UCOORD	U coordinate of data (m)
VCOORD	V coordinate of data (m)
STA_INDEX	Station numbers
FLAG	Flag

OI_T3 Table (OIFITS)

TARGET_ID	Target number
TIME	UTC time of observation (s)
MJD	Modified Julian Date
INT_TIME	Integration time (s)
T3AMP	Triple Product Amplitude
T3AMPERR	Error in Triple Product Amplitude
T3PHI	Triple Product Phase in degrees
T3PHIERR	Error in Triple Product Phase in degrees
U1COORD	U coordinate of baseline AB in triangle (m)
V1COORD	V coordinate of baseline AB in triangle (m)
U2COORD	U coordinate of baseline BC in triangle (m)
V2COORD	V coordinate of baseline BC in triangle (m)
STA_INDEX	Station numbers
FLAG	Flag

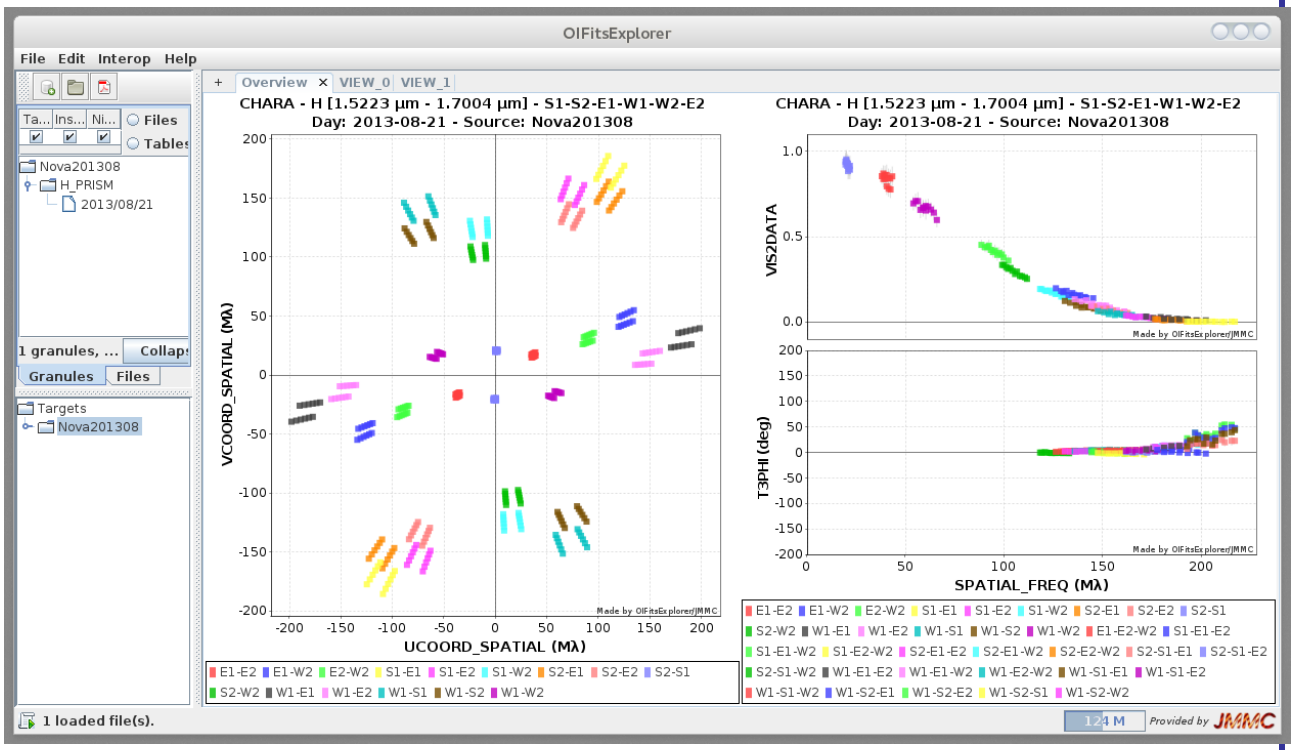
Software for Reading/Writing OIFITS Files

- OIFITSlib – C Library
  - https://github.com/jsy1001/oifitslib
- IDL OIFITS Library – by John Monnier
  - http://dept.astro.lsa.umich.edu/~monnier/oi_data/
- OIFITS Explorer – by JMMC
  - http://www.jmmc.fr/oifitsexplorer_page.htm
- OITOOLS.jl – in development by Fabien Baron
  - Data visualization and modeling (Julia)

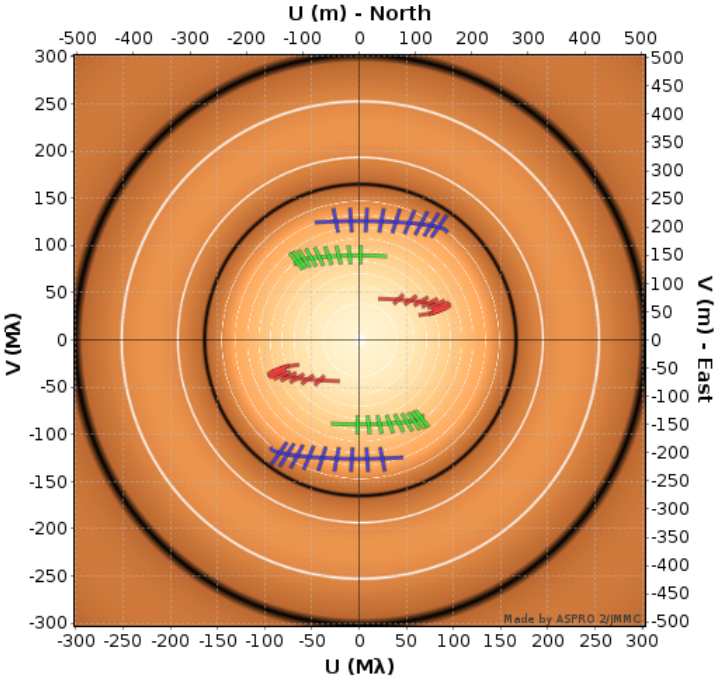
OIFITS Explorer

JMMC

- Visualization
- Load OIFits files
- Plots:
  - uv coverage
  - V2, T3, ...
  - HA, PA, SNR
- Future:
  - Editor: flag and export merged OIFITS files
  - Better data selection graphically



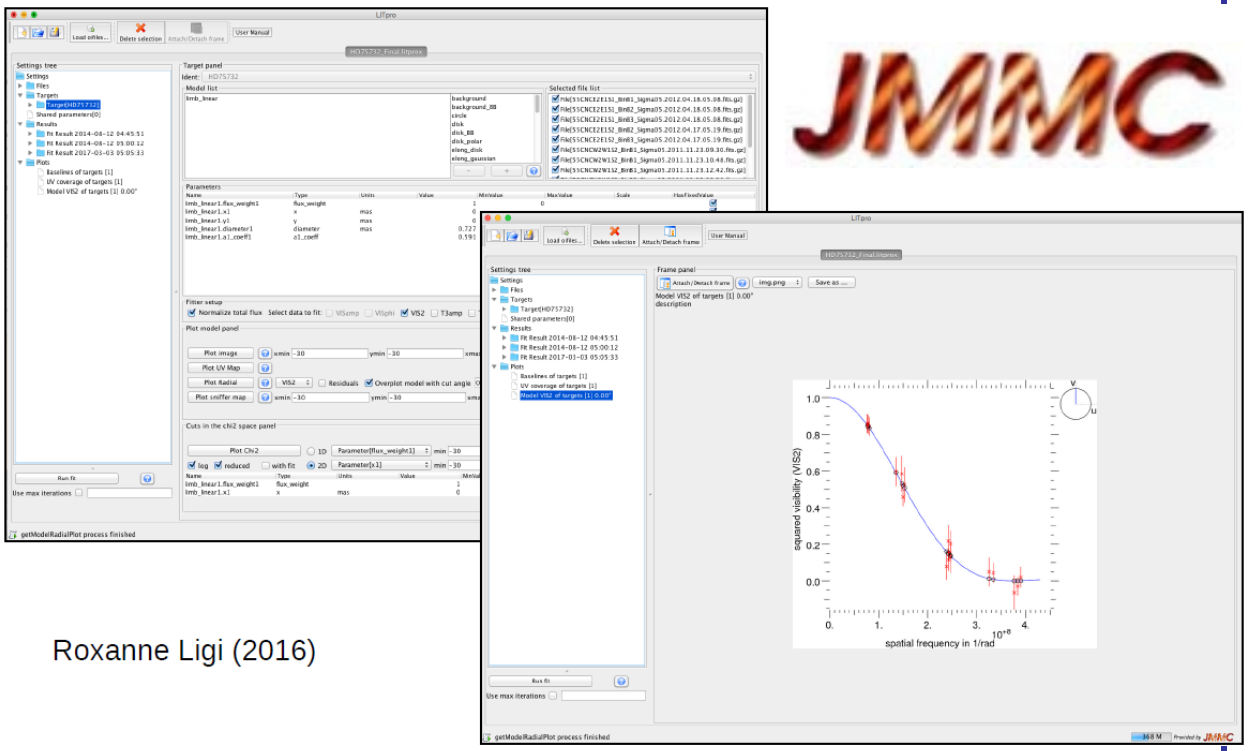
Data Analysis



- Interferometers measure the Fourier Transform of the brightness distribution
- Sparse sampling
- Geometric model fitting
- Physical models
- Image reconstruction

Model Fitting: LITpro

- Fit geometric and limb-darkened models
- Plots to visualize data, models, and results of fits
- Tools to find global minimum

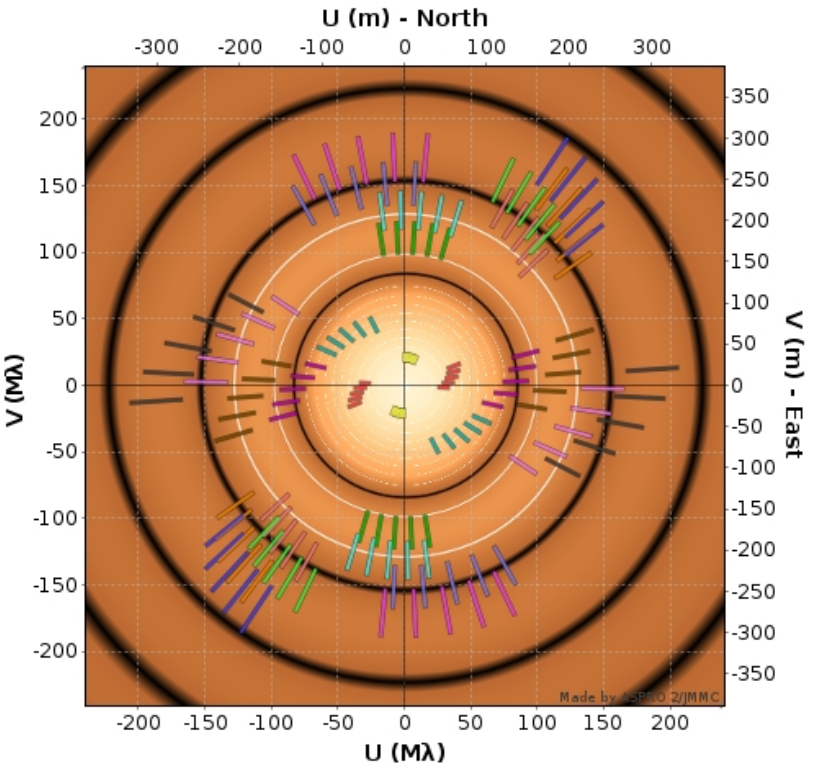


Roxanne Ligi (2016)

LITpro

http://www.jmmc.fr/litpro_page.htm

Image Reconstruction



- Sparse sampling of Fourier frequencies in plane of sky
- Inverse Fourier transform to obtain image
- Compromise between:
  - Fitting available data
  - Keeping the image as regular (simple) as possible

Image Reconstruction

Regularized maximum likelihood

$$\boldsymbol{i}_{\mathrm{MAP}} = \underset{\boldsymbol{i}}{\operatorname{argmin}} \left[\chi^2(\boldsymbol{i}) + \mu R(\boldsymbol{i}) \right]$$

Regularization weight

Most probable image

Likelihood term: Comparison of model to data

Regularizer: Helps interpolate missing Fourier data (smoothness, compactness, total variation, maximum entropy)

Image Reconstruction Software

Software	Optimization	Regularizer	Multi-Spectral	Simultaneous Model Fitting
BSMEM	Trust region gradient	Maximum Entropy Method	No	No
MACIM	Simulated annealing	Maximum Entropy Method, Darkness	No	Yes
MiRA	Variable Metric Limited Memory with bound constraints	Many	No	Yes
SQUEEZE	Parallel Tempering	Many	Yes	Yes
PAINTER	Alternating Direction Method of Minimizers	Many	Yes	No

Imaging Tutorial

904 Vol. 34, No. 6 / June 2017 / Journal of the Optical Society of America A Tutorial

Journal of the Optical Society of America A
OPTICS, IMAGE SCIENCE, AND VISION

Principles of image reconstruction in optical interferometry: tutorial

ÉRIC THIÉBAUT[1,*] AND JOHN YOUNG[2]

[1]University of Lyon, University Lyon 1, ENS de Lyon, CNRS, Centre de Recherche Astrophysique de Lyon UMR5574, F-69230, Saint-Genis-Laval, France
[2]University of Cambridge, Cavendish Laboratory, JJ Thomson Avenue, Cambridge CB3 0HE, UK
*Corresponding author: eric.thiebaut@univ-lyon1.fr

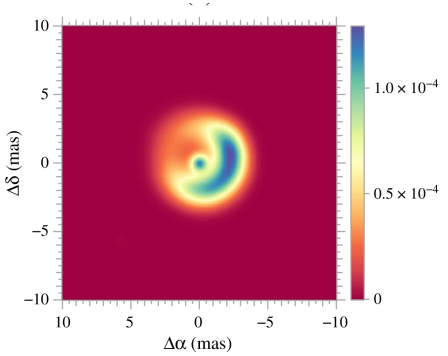
JMMC is developing a common interface for “classic” image reconstruction software

http://www.jmmc.fr/oimaging.htm

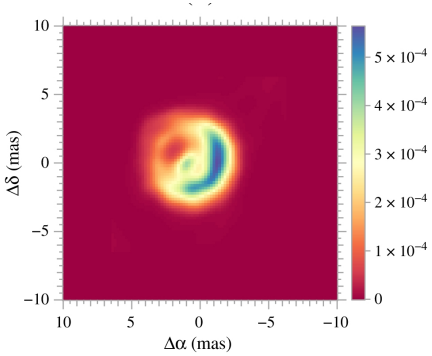
Different Reconstruction Methods and Regularizers

Thiebaut & Young (2017)

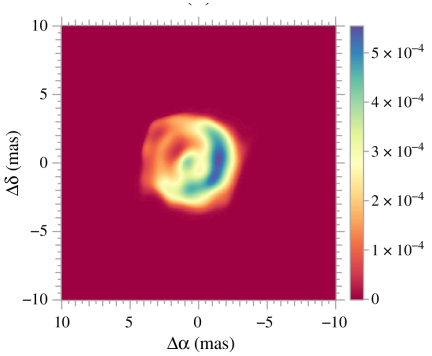
Original Image (LkHα 101)

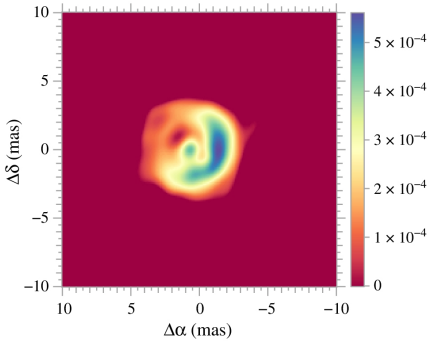


BSMEM

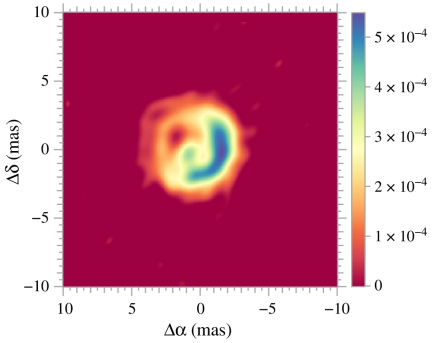


MiRA + MEM regularizer

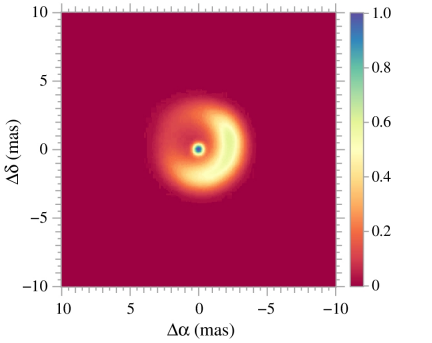




MiRA + compactness quadratic



MiRA + edge-preserving



SQUEEZE with l_0 norm wavelet coefficients

Guides to planning observations available on the CHARA website:

http://www.chara.gsu.edu/observers/applying-for-chara-time
http://www.chara.gsu.edu/observers/planning-an-observation

Links for modeling and imaging software available on the CHARA website:

http://www.chara.gsu.edu/analysis-software/