

NASA Exoplanet Science Institute

Visibility Modeling Tool (VMT) User's Guide

Version 2.0

April 2009

Document Custodian: Mike Papin



NASA Exoplanet Science Institute
Visibility Modeling Tool (VMT) Release 2.0
User's Guide

Prepared By:

Mike Papin
NExSci Engineer

Approved By:

Rafael Millan-Gabet
NExSci Scientist

David Imel
NExSci Manager

DOCUMENT CHANGE LOG

Change Number	Change Date	Pages Affected	Changes / Notes
0.9 Draft	19 Oct 2007	All	Initial Draft
1.0	11 Dec 2007	All	Release 1.0
2.0	27 Apr 2009	All	Release 2.0

COPYRIGHT NOTICE

The Visibility Modeling Tool is copyrighted software.

The VMT contains software packages subject to license agreements other than that of the Copyright license below. Specifically the VMT utilizes:

- 1) JFreeChart, an "open source" library Copyright 2000-2007 by Object Refinery Limited and Contributors. Its use is permitted in proprietary applications under the GNU Lesser General Public License (LGPL).
- 2) JFreeChart is dependent upon and distributed with the JCommon library, also licensed under the GNU Lesser General Public License (LGPL).
- 3) The Apache Commons project copyrighted by the Apache Software Foundation and made available under the Apache License.

All other portions of the VMT are copyrighted under the following copyright notice.

Copyright 2004 - 2007 California Institute of Technology. Developed with U. S. Government sponsorship under contract with the National Aeronautics and Space Administration. All Rights Reserved.

For questions or comments about this software, please email us at: help@ipac.caltech.edu or visit our help desk: http://msc.caltech.edu/contact/help_desk.html

Permission to use, copy and distribute this software and its documentation for academic and/or research purposes, without fee and without a written agreement is hereby granted, provided that the above copyright notice, this paragraph and the following three paragraphs appear in all copies. Reuse of all or part of the software contained here for commercial purposes is strictly prohibited.

The California Institute of Technology makes no proprietary claims to the results, prototypes, or systems supporting and/or necessary for the use of the research, results and/or prototypes for academic and/or non-profit research uses only. However, to the extent that any software and system built in collaboration with industry partners may incorporate proprietary designs of the industry partners, it is possible that certain restrictions may be imposed on the proprietary information

Results received from this tool are designed for non-profit, scientific or experimental purposes only, and is an approximation based on information entered. In no event shall California Institute of Technology be liable to any party for direct, indirect, special, incidental or consequential damages, including lost profits, arising out of the use of this software and its documentation, even if the California Institute of Technology has been advised of the possibility of such damage.

The California Institute of Technology specifically disclaims any warranties, including the implied warranties or merchantability and fitness for a particular purpose. The software and documentation provided hereunder is on an "as is" basis, and the California Institute of Technology has no obligations to provide maintenance, support, updates, enhancements or modifications.

Table of Contents

1. INTRODUCTION.....	6
1.1 PURPOSE & SCOPE.....	6
2. ACCESSING THE VMT VIA THE WEB.....	7
3. DOWNLOADING THE VMT EXECUTABLE	8
4. USING THE VMT	10
4.1 OVERVIEW.....	10
4.2 STARTING THE VMT	11
4.3 FILE PULLDOWN MENU.....	12
4.4 CONTROL PANELS	13
4.4.1 <i>Mode Selection Panel</i>	13
4.4.2 <i>Site/Baseline Selection Panel</i>	14
4.4.3 <i>Target Model Parameter Panel</i>	14
4.4.4 <i>Single Component Parameter Panel</i>	14
4.4.5 <i>Target Model Components Panel</i>	16
4.4.6 <i>Upload Image Panel</i>	16
4.4.7 <i>Plot Content Selection Panel</i>	18
4.4.7.1 <i>Observable Selection</i>	18
4.4.7.2 <i>Model Selection</i>	19
4.4.7.3 <i>Other plotting options</i>	19
4.4.8 <i>Instrument Parameter Panel</i>	19
4.4.9 <i>Wavelength Parameter Panel</i>	19
4.4.10 <i>Observation Parameter Panel</i>	20
4.4.11 <i>Calibrated Data Overlays (OI-FITS)</i>	20
4.5 DISPLAY TABS	20
4.5.1 <i>Plot Tab</i>	20
4.5.1.1 "Properties" Option	21
4.5.1.2 "Save" and "Print" Options	22
4.5.1.3 "Zoom In" and "Zoom Out" Options	22
4.5.1.4 "Auto Range" Option.....	22
4.5.2 <i>Simulated Data Tab</i>	23
4.5.3 <i>Model Tab</i>	23
4.5.4 <i>Instrument Tab</i>	24
4.5.5 <i>FITS Tab</i>	24
4.5.6 <i>OI-FITS Tab</i>	25
4.5.7 <i>Image Tab</i>	26
4.5.8 <i>2D Vis Modulus Tab</i>	27
4.5.9 <i>Nuller Response Tab</i>	28
5. GETTING HELP	29
A. FILE FORMATS	30
B. ALGORITHMS	32
C. ACRONYMS / GLOSSARY	40
D. ACKNOWLEDGEMENTS	41

1. Introduction

1.1 Purpose & Scope

The **Visibility Modeling Tool** (VMT) is a software application developed by the NASA Exoplanet Science Institute (NExSci) to allow prospective or experienced users of optical interferometers to model the interferometric observables for objects of interest using a simple interface. The VMT is a new component on the NExSci's **getCal** suite of observation planning utilities. Among its primary motivations, the VMT aims to support users of the Keck Interferometer (KI), and in particular the Nuller Key Science users. However, it should be equally useful to users of any other ground-based interferometer. The VMT performs visibility amplitude (and null depth in the case of the KI) predictions, and thus will help astronomers primarily in the observation planning stage of their investigations.

At a glance, the main new capabilities of the VMT's current release (version 2) are:

- Allows users to upload arbitrary brightness maps (in FITS format).
- Permits user data upload (in OI-FITS format) for plotting alongside models.
- Provides more realistic treatment of the Keck Interferometer Nuller beam pattern.

These capabilities extend the capabilities of the previous (version 1) release:

- All operating ground-based interferometers are supported. The user can select any baseline or group of baselines.
- Allows the user to approximate a surface brightness of interest by combining any number of elementary morphologies (point source, uniform disk, Gaussian disk and uniform ring).
- Each elementary brightness component can have a user-specified fraction of the total flux. If the flux fractions in the elementary components do not add up to 1.0, the remainder flux is assumed to be completely incoherent.
- Each elementary brightness component can have an arbitrary RA and DEC offset with respect to the phase center.
- The disk morphologies (uniform, Gaussian and ring) can have elliptical shapes, in order to approximate common objects of interest such as elongated stars or inclined circumstellar disks.
- Computes visibility modulus for a composite or elementary object, or for a selected component of a composite object.
- For the Keck Interferometer Nuller, also computes an approximated Null Depth.
- Supports monochromatic, broadband or spectrometer visibilities.

In incremental upgrades, we envision growth of the VMT in the following main areas:

- Allow users to upload arbitrary spectra for the elementary components.
- Compute other interferometric observables, such as closure and differential quantities.
- Support of the OI-FITS data format for output of simulated data.
- Enable astrometric observables.
- Provide model fitting capability.

2. Accessing the VMT via the Web

The VMT can be accessed over the web as an applet that runs in the context of a web browser. The VMT is supported by most browsers such as Safari, Internet Explorer, and Mozilla Firefox, and is located at: <http://nexsciweb.ipac.caltech.edu/vmt/vmtWeb/>.

For security reasons, the JRE does not allow applets certain privileges by default, such as access to your computer's file system unless you explicitly grant it. Before you can access the applet, you will be prompted with the option to either "Trust" or "Don't Trust" the applet.



To allow the applet full access to your file system, you must grant it access by selecting the "Trust" option. Selecting the "Don't Trust" option will still bring up the applet interface, but you will not be presented with dialogue boxes to browse your file system when attempting to load or save files.

After responding to the certification dialogue, the "Start VMT Applet" button will appear on the browser page (may take a few moments). Pressing the "Start VMT Applet" button starts the downloading process of the applet to your local machine. The process consists of 3 steps:

- 1) the applet gets downloaded to your local machine,
- 2) the JRE (Java Runtime Environment) is started up on your machine (if not already running)
- 3) the JRE starts up the application.

Downloading the applet for the first time (or when an updated version is deployed on the server) will take a few moments. If a red X appears in the applet button on the web page, your machine either does not have Java installed, or your browser is not configured correctly to run the applet (i.e. requires a plugin).

The VMT requires JRE version 1.4 or higher. To test your machine's configuration for compatibility with the VMT, there are websites that can help such as www.javatester.org. This web site addresses four Java issues:

- 1) Is your web browser Java enabled?
- 2) If so, what version of Java is it using?
- 3) How to install and upgrade Java, and
- 4) Configuring the Java options in your browser.

3. Downloading the VMT Executable

The VMT can be downloaded as an executable JAR (Java Archive File) file within a .zip file from the NExSci download site at <http://nexsciweb.ipac.caltech.edu/software/>. For assistance with accessing the download site, please use our help desk web form at <http://nexsciweb.ipac.caltech.edu/cgi-bin/helpdesk/helpdesk.cgi>

Your computer must have a compatible Java Runtime Environment (JRE) version installed (1.4 or higher). You can check your java version at www.java.com and download the appropriate version if necessary.

Downloading and Installing JAI:

To upload images, your Java system must be extended with the **Java Advanced Imaging (JAI)** application interface (API) which supports image manipulation for Java applications and applets. To download JAI, go to <http://java.sun.com/products/java-media/jai/current.html>. For specific installation instructions, click the "Documentation" link under the "Reference" heading on the left side of the page.

Once a compatible version of Java is installed on your computer:

- 1] Locate and click the "download" link next to VMT Tool
- 2] Then, depending upon your platform:

MacOSX:

- a) save the vmt-x.y.zip file to a desired location on your machine
- b) locate the zip folder on your machine and extract it (double-click). Your version of MAC OS may do this step automatically.
- c) locate the executable jar icon (vmt-x.y.jar) within the unzipped folder and double-click it.

Windows:

- a) save the vmt-x.y.zip file to a desired location on your machine
- b) locate the zip folder on your machine, and extract it (right click->Extract All..)
- c) locate the executable jar icon (vmt-x.y.jar) within the unzipped folder and double-click it.

Linux:

- a) save the vmt-x.y.zip file to a desired location on your machine
- b) locate the zip folder on your machine, and extract it (right click->Extract Here)
- c) in terminal window, locate vmt-x.y.jar executable jar file within the unzipped folder
- d) launch it from the command line: `java -jar vmt-x.y.jar`

To start your first VMT session, the VMT Session File example can be read into the executable under the "File->Read VMT Session File" menubar pull-down found in the upper-left-hand-side of the control panel.

Increasing JVM Memory:

Upon startup, the initial memory allocated to the application by the JVM may not be sufficient enough for processing large (large than 512x512 pixels) images. If you are attempting to load a large image and encounter an "Out of Memory" message, you will have to exit the VMT and restart the JVM with a parameter directing the JVM to allocate more memory to the application.

The steps to increase VMT memory varies according to platform you are using:

MacOSX:

- a) Exit out of the VMT application
- b) Open a terminal window (Applications->Utilites->Terminal.app) to get a command line prompt. Locate the vmt jarfile and enter:

```
java -Xms128m -Xmx256m -jar location/vmt.x.y.jar
```

Windows:

- a) Exit out of the VMT application
- b) Open up the Windows Control Panel
- c) Locate the Java Control Panel and double-click
- d) Select the "Java" Tab
- e) Click the first "View..." button
- f) Add **-Xms128m** and **-Xmx256m** to the Java Runtime parameter for each JVM listed in the Java Runtime Settings dialog.
- g) Click OK to close the panels
- h) Restart the VMT application

Linux:

- a) Exit out of the VMT application
- b) Open a Linux terminal window to get a command line prompt, locate the vmt jarfile and enter:

```
java -Xmx256m -jar location/vmt.x.y.jar
```
- c) Restart the VMT application

KNOWN ISSUE(S):

1] VMT sessions which contain uploading sequential large images may cause the VMT to indicate that the VMT has run out of memory. If the image is larger than 512x512 pixels, make sure the memory has been increased (see section "Increasing JVM memory for your platform). If the image is 512x512 pixels or less, the VMT may be in a state in which the Java Runtime Environment needs to be exited and restarted.

Workaround:

For the VMT application, simply exit the VMT and restart it. If you are using the VMT applet, under the pull down menus, there is a "Exit Java" option under the Help pull down menu.

4. Using the VMT

4.1 Overview

The Applet and downloadable executable user interfaces are identical in their layouts. The VMT GUI layout has three main components:

1. Controls on left side of the GUI that allow the user to specify the interferometer, baseline, and target to be simulated.
2. Controls on the right side of the GUI that allow the user to select which observables are to be displayed and the time cadence of the simulation.
3. Main display in the center of the GUI for viewing the predicted simulated observables (both in graphical and textual formats) and summary information about the target and instrument being simulated. Tabs at the top of this display also allow the user to customize the control panels to the user's preference, and to access help via an application index.

1. The left control panels are made up of the following sub control panels:

- Mode Selection Panel ("Analytical Models" or "Image Upload")
- Site/Baseline Selection Panel
- Target Model Parameter Panel
- In "Analytical Models" mode:
 - Target Model Components Panel
 - Single Component Parameter Panel
- In "Upload Image" mode:
 - Image Upload Parameter Panel
 - Image upload button and image display

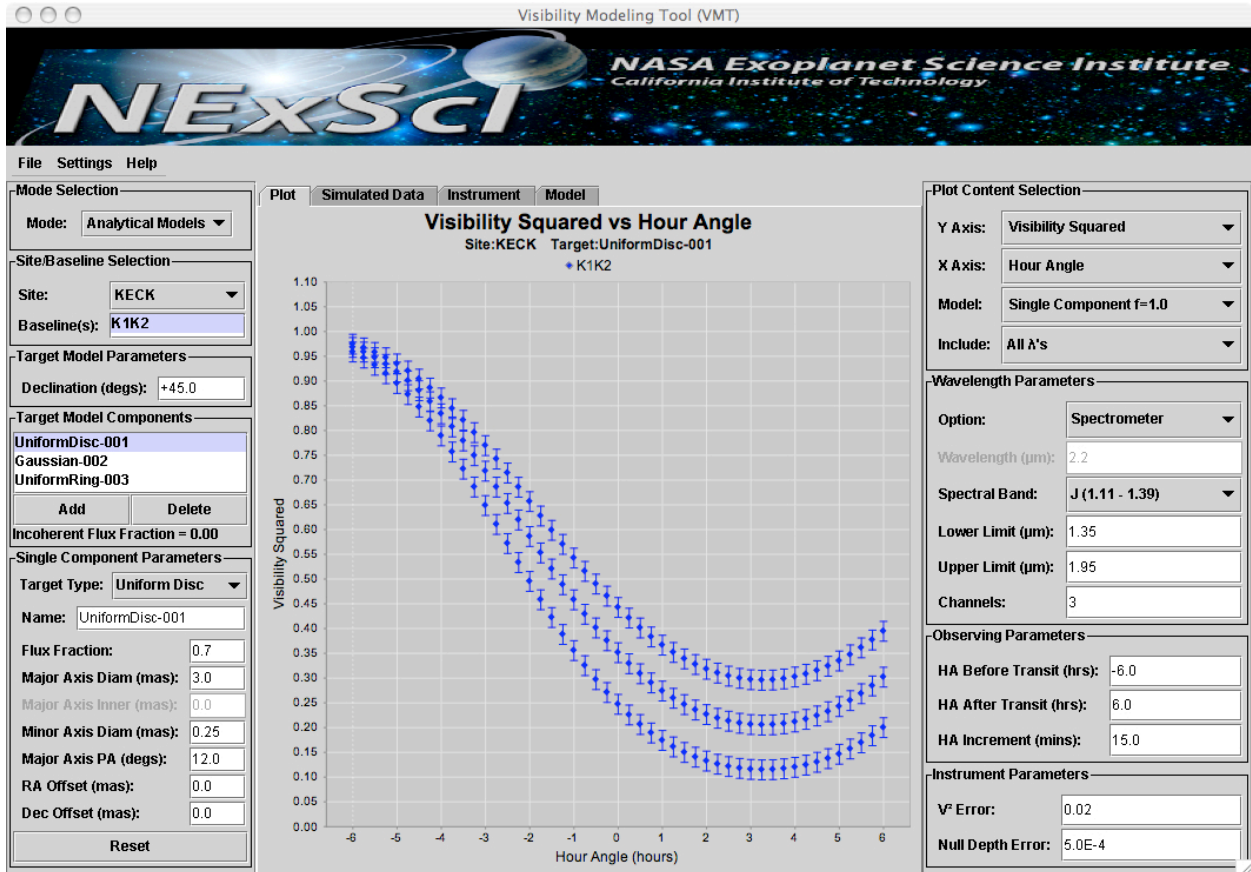
2. The right control panels are made up of the following sub control panels:

- Plot Content Selection Panel
- Wavelength Parameters Panel
- Observing Parameters Panel
- Instrument Parameters Panel

3. The middle display panel includes the following tabs:

- In "Analytical Models" mode:
 - Plot: shows a line plot with X & Y axis quantities determined by choices in the Plot Content Selection Panel (see 2 above).
 - Simulated Data: simulated data in ASCII format.
 - Instrument: Summary of the instrument and observing parameters chosen.
 - Model: description of the target model constructed.
- In "Upload Image" mode:
 - Plot: Same as above.
 - Simulated Data: Same as above.
 - Instrument: Same as above.

- FITS: Shows header and displays image data in user uploaded FITS brightness image.
- Image: Displays the user uploaded FITS brightness image.
- 2D Vis Modulus: Displays the 2D visibility of the user uploaded FITS brightness image, with overlaid u & v points corresponding to the interferometer and observing parameters chosen.
- Nuller Response (for KI only): Displays the 2D “beam pattern” of the KI Nuller, including an option to overlay the target brightness image.
- OI-FITS (only if an data file has been uploaded): shows headers and data in user uploaded data file in OI-FITS file.



Visibility Modeling Tool GUI Layout

Each of the sub panels is described in further detail in subsequent sections. The center display panel is composed of many tabs allowing the user to select various options to view the calculated observables in both graphical and textual formats. The Preferences Tab allows the user to modify the layout of these control sub panels.

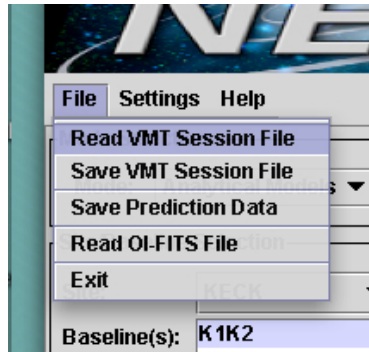
4.2 Starting the VMT

In order to begin using the VMT, a target model must first be created (or read in from a .vmt disk file if previously created and saved to disk, or uploaded from a FITS file containing a brightness image). The default behavior for the VMT is to start up in Analytical Model Mode. The observables are immediately displayed in the center plot tab based upon the initial default settings of the control panels. Upon modification of various parameters within the control panels, the resident model is immediately

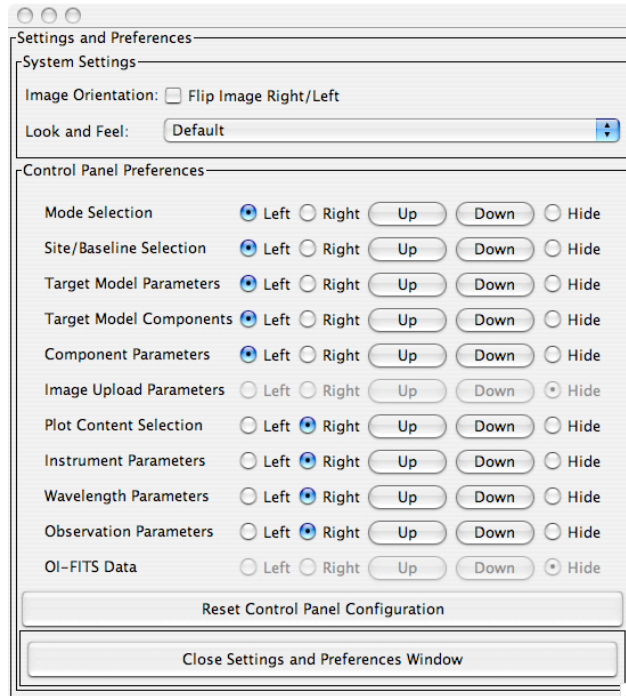
recalculated and its observables displayed. The functionality of these control panels is described in the subsequent sections.

4.3 File Pulldown Menu

The VMT pulldown menu items consist of “File”, “Settings”, and “Help”. The “File” Pulldown Menu Option allows the user to restore a previous VMT session by loading in a VMT session file (VMT session files have a .vmt extension), save the current VMT sessions, save the predicted simulation data to a file, read an OI-FITS file to overlay the current simulated data and exit the VMT application.



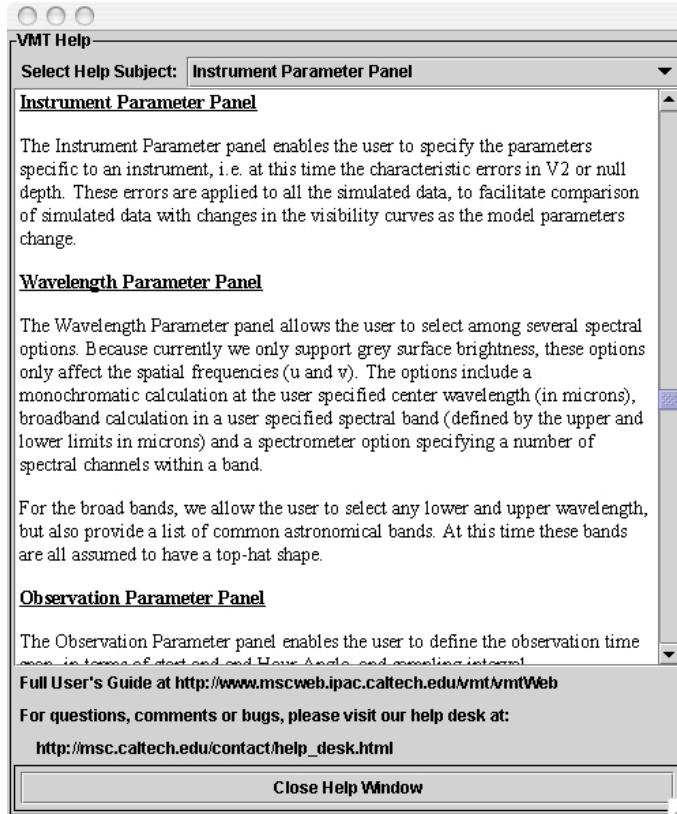
The “Settings” option allows the user to set system settings and user preferences. The “System Preferences” section contains a checkbox which allows the user to flip an uploaded image to orient it to the VMT assumed orientation “east is left”. The Look and Feel of the overall GUI is also available to be set.



The “Control Panel Preferences” section allows the user to customize the configuration of the sub control panels in the left and right control panels. The placement of each sub panel can be customized by moving it to the left or right side of the GUI, moving it up or down within either the left or right control

panel, or hiding it from the GUI altogether. The initial default configuration for the Control Panel can be restored by pressing the “Reset Control Panel Configuration” button.

The “Help” option provides help for using the VMT in which the user can select from a list of topics in the “Select Help Subject:” pull-down menu.

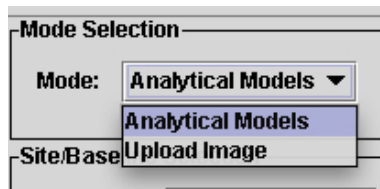


Also under the “Help” option is an “About” tab that provides information regarding the VMT application, it’s environment as well as third party software (and their licenses) that it incorporates.

4.4 Control Panels

4.4.1 Mode Selection Panel

The user can establish a target model by either selecting “Analytical Model”, or “Upload Image” in the “Mode Selection Panel”.



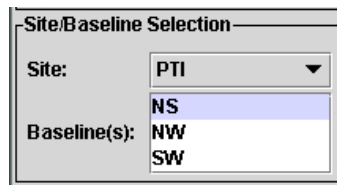
In the “Analytical Model” mode, the VMT provides the “Single Component Parameter” panel that supports the creation of the single component brightness models (point source, uniform disk, Gaussian or uniform disk), as well as the “Target Model Component Parameter” panel that allows the creation of linear combinations of these elementary components. Upon starting up the VMT, a default target is selected

(initially a uniform disc, but can be changed), with parameters initialized to zero. The user can then modify these values via the Single Component Parameters panel, select a different component from the Target Type pull-down menu, or construct a composite model using the “Add” and “Delete” buttons in the Target Model Components Panel. In the case of a composite model, the observables plotted correspond to the currently highlighted component in the list or to the global model, via plotting controls described later in this manual.

In the “Upload Image” mode, the VMT displays the “Upload Image” panel. This panel supports the uploading of arbitrary brightness models from a FITS formatted file specifying an image of the object of interest and a specification of the image pixel scale (i.e. milli-arcsec/pixel). **The VMT does not attempt to read the pixel scale or image orientation from the input FITS file.** This panel is further described in the following sections.

4.4.2 Site/Baseline Selection Panel

The Site/Baseline Selection panel allows the user to select an interferometer location and its associated baseline(s). The currently supported interferometers are KECK, PTI, NPOI, CHARA, VLTI and SUSI.



Upon selection of an interferometer, all associated baselines are displayed in the “Baseline(s)” list. The first baseline in the list is selected as the default. The user can select any baseline in the list, a contiguous subset of baselines, or all the baselines by clicking on any baseline, holding down the **Shift key** and selecting another baseline. Each baseline plot can be either displayed or hidden by holding down the **Control key** and clicking on the desired baseline in the menu. All selected baselines are plotted simultaneously on the “Plot” tab in the center display panel.

NOTE: Nulling observables are only enabled and calculated for the Keck Interferometer.

4.4.3 Target Model Parameter Panel

In “Upload Image” mode, the Target Model Parameter panel allows the user to specify parameters that apply to the composite model as a whole, i.e. the phase center declination only at this time.

4.4.4 Single Component Parameter Panel

In “Analytical Mode”, the Single Component Parameter Panel enables the user to enter/modify parameters for each target type. The user can select one of the morphologies using the “Target Type” pull-down menu. The panel will configure itself to allow the user to enter/modify the relevant parameter values specific to that morphology.

The tool currently supports four morphologies: Point Source, Uniform Disc, Uniform Ring, and Gaussian. .

Parameters common to all of the component morphologies are:

- Name specifies the name of the model component and can be any string of up to 20 characters
- RA Offset specifies the component's Right Ascension offset with respect to the phase center (milliarcseconds)
- Dec Offset specifies the component's Declination offset with respect to the phase center (milliarcseconds)
- Flux Fraction specifies the component's fractional contribution to the total flux

NOTE: the sum of the flux fractions assigned to all components in a composite model must be less than or equal to 1.0. If the sum of the flux fractions is less than 1.0, the remainder flux is assumed to be completely incoherent.

The non-point source morphologies (i.e. Uniform Disk, Gaussian, and Uniform Ring) contain additional parameters that describe their size and shape:

Uniform Disk and Gaussian:

- Major Axis Diameter specifies the angular diameter of the major axis (milliarcseconds)
- Minor Axis Diameter specifies the angular diameter of the minor axis (milliarcseconds). This is different than the major axis diameter for elliptical morphologies.
- Major Axis Position Angle specifies the orientation of the elliptical brightness distribution, via the position angle of the major axis, measured East of North (degrees)

Uniform Ring:

- Major Axis Inner Diameter specifies the ring inner angular diameter along the major axis (milliarcseconds)
- Major Axis Outer Diameter specifies the ring outer angular diameter along the major axis (milliarcseconds)
- Minor Axis Outer Diameter specifies the inner ring angular diameter along the minor axis (milliarcseconds). This is different than the major axis outer diameter for elliptical morphologies.

Major Axis Position Angle specifies the orientation of the elliptical brightness distribution, via the position angle of the major axis, measured East of North (degrees)

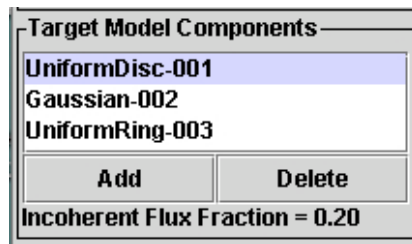
The “Reset” button allows the user to cancel all the modified target parameters of the selected target and revert all parameters to the values they were in upon initially selecting the target for modification (or in the case of adding a target, to the original default values).

4.4.5 Target Model Components Panel

The Target Model Component Panel lists all of the components currently defining a composite. It also tracks the total fractional flux, and assigns any remaining flux as a completely incoherent component. The component that is highlighted is the one displayed in the “Single Component Parameters” panel and can be modified simply by changing any of the values. The changes are immediately saved and reflected in the data output and plots.

To delete a target in the model, select it from the Target Component Model list and press the delete button. The deletion is immediately reflected in the composite model and cannot be undone.

Additional target components can be added by pressing the “Add” button on the panel. This causes a new default target component to be added to the composite model and displayed in the “Single Component Parameters” panel. The user can then modify the added target component.



NOTE: Optical interferometers require fringe tracking on a bright compact component, which effectively becomes the phase center. It is the user's responsibility to construct a composite model that satisfies this requirement. Also, real interferometers have field of view limitations, and the user must be mindful of this when constructing a very extended object or one that contains components placed at large RA and DEC offsets.

4.4.6 Upload Image Panel

The user can bring up the “Upload Image” panel by selecting the “Upload Image” option in the “Mode Selection” panel. The panel allows the user to upload an arbitrary brightness image by selecting a FITS file from the users local disk. The panel displays a “No Image Available” message (Figure A) until the user successfully selects and reads a FITS image from a FITS-formatted file.

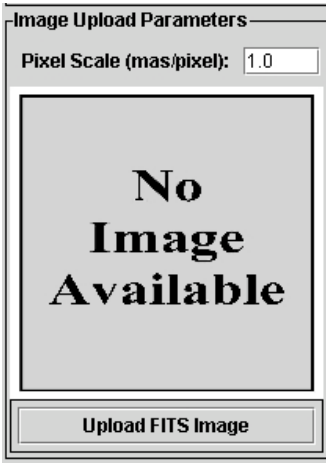


Figure A

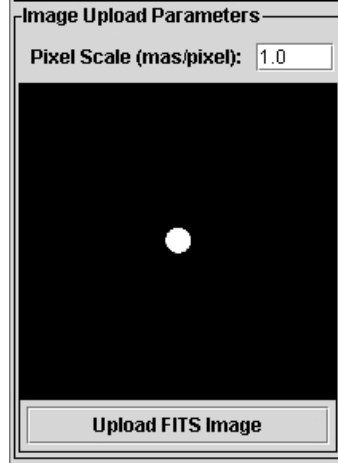


Figure B

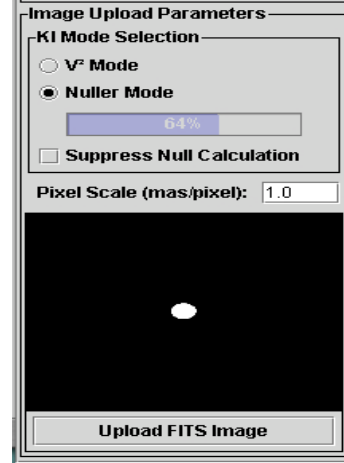


Figure C (KI only)

Pressing the “Upload FITS Image” button brings up a file selection dialog box that allows the user to browse for the FITS file to be uploaded. The “No Image Available” message is then replaced by the uploaded brightness image (figure B). The user must specify the pixel scale of the image by entering it (in units of milli-arcsec/pixel) in the Pixel Scale input box.

NOTE: the FITS format supports some standard, but optional, keywords to specify the image plate scale and sky coordinates. However, the VMT does not require the presence of these optional keywords; in the current version, it does not read them even if they are present. The pixel scale must be entered by the user in the Pixel Scale input box, as described above, and the image orientation is assumed to be: East = Left, North = Up. The input image can also be flipped left-to-right via a checkbox in the Preferences tab.

Currently, the VMT is limited to uploading FITS images of at most 512x512 pixels in size, unless the JVM memory is increased as described above. If an uploaded image does not have a number of pixels that is a power of 2, the VMT will zero-pad around the input image to the nearest power of 2.

When the Keck Interferometer is selected, the Image Upload Panel displays a KI Mode Selection Panel (figure C) in which the user can select either of two modes, the visibility mode (“V² Mode”) or the Keck nuller mode (“Nuller Mode”).

In Visibility (V²) Mode, the VMT:

- 1] disables the Null Depth observable option in the Plot Tab.
- 2] disables the Null Depth Error field in the Instrument Parameter Panel.
- 3] sets the Null Depth data to “null” in the Simulated Data Tab.

In Keck Nuller Mode, the VMT:

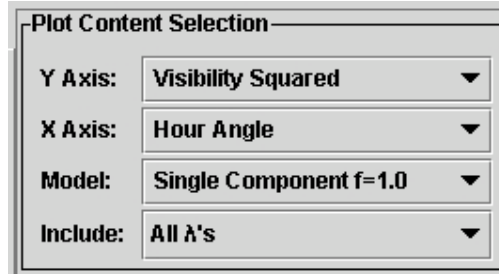
- 1] disables the Visibility Modulus and Visibility Squared observable options in the Plot Tab.
- 2] may modify parameters in the Wavelength Parameters Panel valid to KI Nuller Defaults .
- 3] disables the Visibility Squared Error field in the Instrument Parameter Panel.
- 4] sets the Visibility Squared data to “null” in the Simulated Data Tab.

Because the Nulling observables for the Keck Interferometer require a time consuming calculation, a suppression option is also provided in this case. When selected, all subsequent nuller calculations are suppressed. When deselected, the nuller calculation is immediately calculated and for each subsequent modification to any control panel input. A progress bar is provided to inform the user of the progress of

the nuller calculation. The length of the nuller calculation is dependent upon the number of hour angle observation points specified and number of spectral channels. If these parameters are reduced, the nuller calculation is quicker.

4.4.7 Plot Content Selection Panel

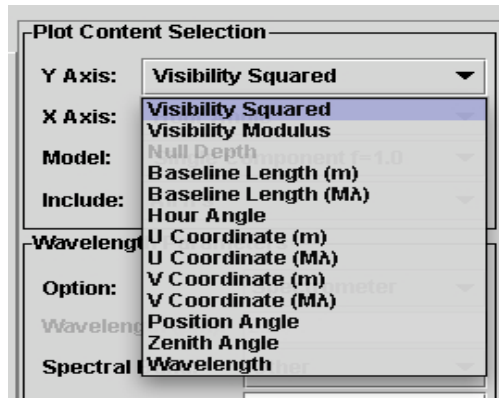
The “Plot Content Selection” panel allows the user to select the content of the displayed observables. This panel is enabled only when the Plot Tab is displayed.



4.4.7.1 Observable Selection

The “Plot Content Selection” panel allows the user to customize the plot content by selecting one of the following observables on either axis:

- Visibility Squared
- Visibility Modulus
- Null Depth (for KI only)
- Baseline Length (in meters)
- Baseline Length (in millions of wavelengths)
- Hour Angle
- U Coordinate (in meters)
- U Coordinate (in millions of wavelengths)
- V Coordinate (in meters)
- V Coordinate (in millions of wavelengths)
- Position Angle (in degrees)
- Zenith Angle (in degrees)
- Wavelength (in microns)



For details on the algorithms employed to calculate these observables, please refer to Appendix B.

4.4.7.2 Model Selection

In “Analytical Models” Mode, the “Model” selection pulldown menu in the Plot Content Selection panel, allows the user to select one of three options to view the observables:

- Single Component computes and displays the selected observables for the component currently highlighted in the Target Model Components panel described earlier, using the fractional flux that was entered by the user.
- Single Component f=1.0 same as above, but places all the flux in this component,
- Composite displays the calculated observables for the composite model.

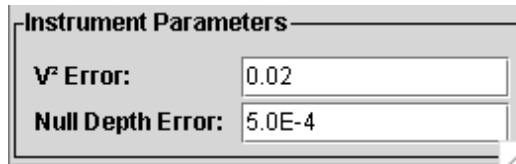
In “Image Upload” Mode, the “Model” selection is automatically set to “FITS Image”.

4.4.7.3 Other plotting options

In order to improve the readability of the plots, when the user specifies the **spectrometer** option in the Wavelength Parameter panel (see 4.4.9 below), the VMT provides the user an “Include” option to plot the selected observable for all the spectrometer wavelengths or for only the middle wavelength. Likewise, if a plot as a function of wavelength is selected, the user has the option to plot the selected observable for all the hour angle samples, the first hour angle sample, the middle hour angle sample, or the last hour angle sample.

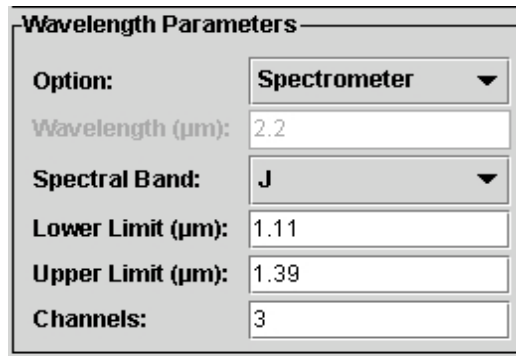
4.4.8 Instrument Parameter Panel

The Instrument Parameter panel enables the user to specify the parameters specific to an instrument. In this version of the VMT these are the characteristic errors in V^2 or null depth. These errors are applied to all the simulated data to facilitate comparison of simulated data with changes in the visibility curves as the model parameters change.



4.4.9 Wavelength Parameter Panel

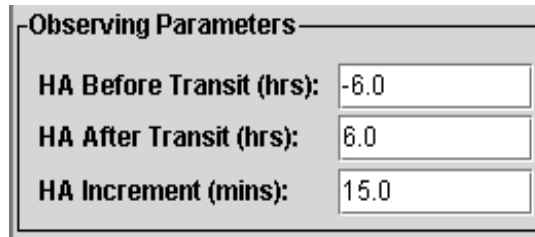
The Wavelength Parameter panel allows the user to select among several spectral options. Because we only support grey surface brightness at present, these options only affect the spatial frequencies (u and v). The options include a **monochromatic** calculation at the user-specified center wavelength (in microns), **broadband** calculation in a user specified spectral band (defined by the upper and lower limits in microns) and a **spectrometer** option specifying a number of spectral channels within a band.



For the broad bands, we allow the user to select any lower and upper wavelength, but also provide a list of common astronomical bands. At this time these bands are all assumed to have a top-hat shape.

4.4.10 Observation Parameter Panel

The Observation Parameter panel enables the user to define the observation time span, in terms of start and end Hour Angle, and sampling interval.



The image shows a screenshot of a software panel titled "Observing Parameters". It contains three input fields with labels and values:

Parameter	Value
HA Before Transit (hrs):	-6.0
HA After Transit (hrs):	6.0
HA Increment (mins):	15.0

4.4.11 Calibrated Data Overlays (OI-FITS)

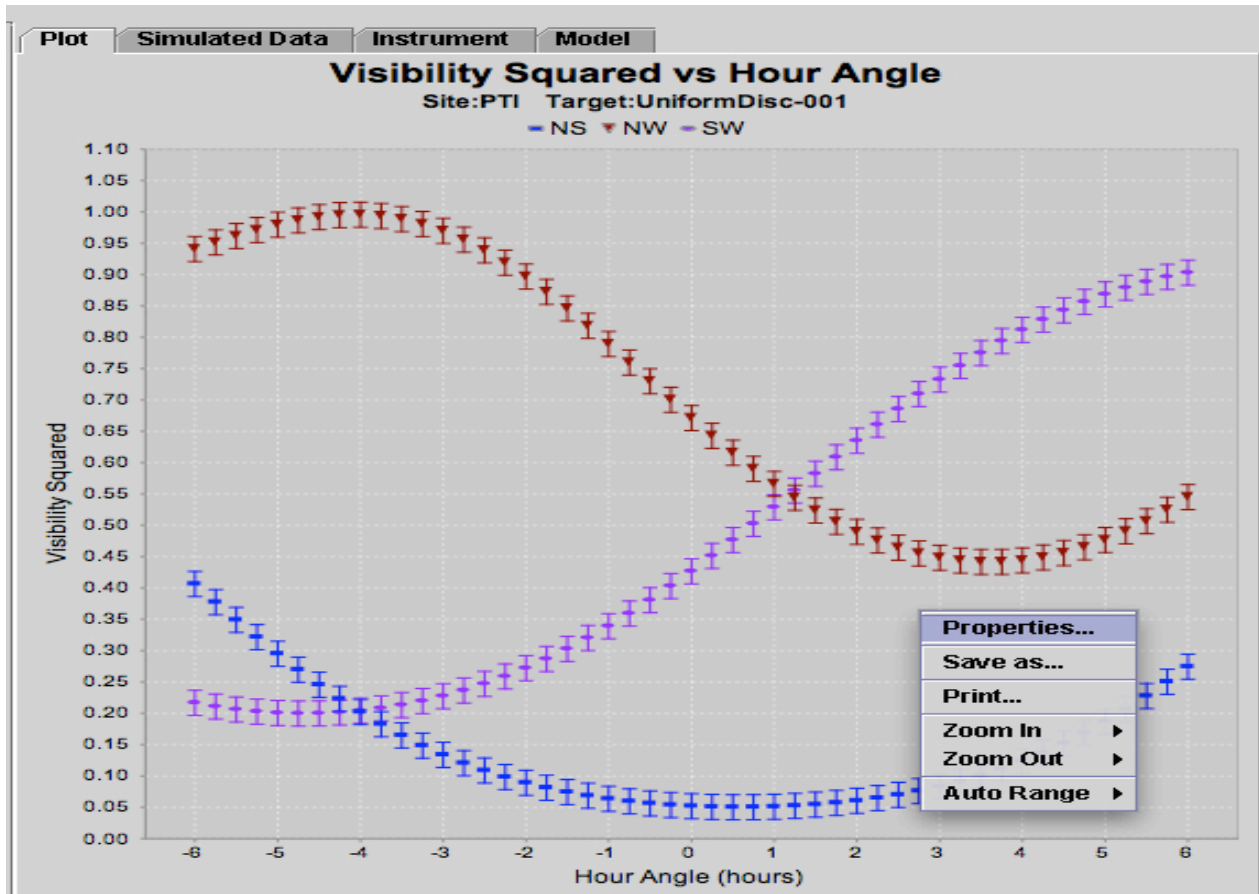
The VMT provides the user with the capability to overlay calibrated data in the OI-FITS format (an IAU standard, see http://www.mrao.cam.ac.uk/research/OAS/oi_data/oifits.html). The "Read OI-FITS File" under the File Pulldown Menu will prompt the user to browse for an OI-FITS formatted file and will parse and overlay the data in the vis and vis² data tables associated with each (details are further described in subsequent sections).

4.5 Display Tabs

The VMT has a center display panel that consists of a number of tab options which allow the user to view the predicted simulated observables (both in graphical and textual formats), summary information about the target and instrument being simulated, and to customize the control panels to the user's preference.

4.5.1 Plot Tab

The plot tab allows the user to view the simulated observables in a plot or graphic context. The user controls the content of the plot in the "Plot Content Selection" panel described in Section 4.4.7.



The plot contains many default settings that can be customized by right clicking on the plot. The user can customize properties such as the title's text, font and color, the plot axes text font, color and range settings, and the plot lines, types, and colors.

4.5.1.1 "Properties" Option

The "Chart Properties" panel can be brought with a right mouse click on the chart and selecting "Properties...". This panel contains the tabs "Title", "Plot" and "Other".

The "Title" tab allows the user to modify the properties of the chart's main title such as the name, the font and color of the title.

The "Plot" tab allows the user to modify the properties of the plot. These properties include the same properties of the main chart title (name, font and color), but for each of the domain and range axes labels. The user can select the "Domain Axis" or "Range Axis" tabs to scale the plot and/or customize the tick mark properties for either the domain or range axes, respectively. The "Appearance" tab allows the user to modify the appearance of the plot including the thickness of the plot line(s), the plot's background color, and plot orientation (vertical or horizontal).

The "Other" tab allows the user to choose whether or not the fonts of the chart are "anti-aliased" relative to the background color of the chart.

4.5.1.2 “Save” and “Print” Options

The “Save as...” and “Print...” options allow the user to save and print the chart in the downloaded executable version of VMT.

4.5.1.3 “Zoom In” and “Zoom Out” Options

The “Zoom In” and “Zoom Out” options allow the user to zoom in or out on the plot for either the range and/or domain axes. The user can also zoom in on the data by left clicking and dragging over a subset of data points to be expanded in a top left to bottom right motion. Dragging the mouse in any of the three alternate ways (top right to bottom left, bottom right to top left or bottom left to top right) causes the data to be re-centered.

4.5.1.4 “Auto Range” Option

The “Auto Range” option turns the automatic scaling feature to be turned on. The right-click->”Auto Range” option is simply a short cut for going through the chart “Properties...” option. To reset the scaling, the user must right mouse click and select ”Properties->Plot->Range/Domain Axis”.

4.5.2 Simulated Data Tab

The “Data” tab provides an ASCII textual representation of the calculated observables in a tabular format. The downloadable version of the VMT provides the capability to save this data in a text file (in the Menu Bar select File->Save Prediction Data). The format of the data file allows for the easy importing into other programs for manipulation. In future releases, we plan to export data also in the IAU standard for optical interferometry (OI-FITS).

HrAngle	Baseline	U(m)	V(m)	Bp(m)	ZA(deg)	PA(deg)	V2(1.65)
-6.00	NS	-59.553	-54.559	80.766	74.042	227.506	0.40099
-6.00	NW	-18.108	21.912	28.426	74.042	320.431	0.93912
-6.00	SW	41.445	76.468	86.978	74.042	28.457	0.21629
-5.75	NS	-61.853	-56.546	83.804	71.202	227.566	0.37255
-5.75	NW	-23.411	21.233	31.606	71.202	312.207	0.94998
-5.75	SW	38.441	77.776	86.757	71.202	26.301	0.21056
-5.50	NS	-63.888	-58.604	86.695	68.325	227.470	0.34477
-5.50	NW	-28.615	20.381	35.131	68.325	305.461	0.96049
-5.50	SW	35.273	78.983	86.501	68.325	24.065	0.20606
-5.25	NS	-65.649	-60.724	89.428	65.415	227.232	0.31786
-5.25	NW	-33.696	19.361	38.862	65.415	299.882	0.97029
-5.25	SW	31.954	80.083	86.223	65.415	21.752	0.20277
-5.00	NS	-67.130	-62.898	91.992	62.474	226.864	0.29203
-5.00	NW	-38.632	18.178	42.695	62.474	295.198	0.97898
-5.00	SW	28.498	81.073	85.935	62.474	19.367	0.20067
-4.75	NS	-68.323	-65.115	94.382	59.506	226.377	0.26742
-4.75	NW	-43.403	16.835	46.554	59.506	291.200	0.98620
-4.75	SW	24.920	81.947	85.652	59.506	16.914	0.19974
-4.50	NS	-69.223	-67.366	96.592	56.513	225.779	0.24417
-4.50	NW	-47.989	15.339	50.381	56.513	287.726	0.99157
-4.50	SW	21.235	82.702	85.385	56.513	14.401	0.19999
-4.25	NS	-69.827	-69.642	98.620	53.497	225.076	0.22239
-4.25	NW	-52.369	13.696	54.130	53.497	284.656	0.99474
-4.25	SW	17.459	83.336	85.145	53.497	11.833	0.20140
-4.00	NS	-70.132	-71.933	100.464	50.461	224.274	0.20213

4.5.3 Model Tab

The “Model” tab (“Analytical Models” mode only) provides a list of all the parameters describing the target model constructed by the user.

Target Name	Target Type	Flux Fraction	Major AxisDiam	Minor AxisDiam	InnerRing AxisDiam	Major AxisPA	RA Offset	Dec Offset
UniformDisc-001	UDisc	0.7	3.0	0.25	N/A	12.0	0.0	0.0
Gaussian-002	Gauss	0.2	1.0	0.3	N/A	28.0	10.0	10.0
UniformRing-003	URing	0.1	0.25	0.1	0.05	43.0	3.4	1.7
component-002	Uninit	N/A	N/A	N/A	N/A	N/A	N/A	N/A

4.5.4 Instrument Tab

The “Instrument” tab provides a summary of the selected instrument configuration.

The screenshot shows a software window with four tabs: Plot, Simulated Data, Instrument (selected), and Model. The main area is titled "Instrument Summary" and contains the following text:

```

INTERFEROMETER:
Name                PTI
Latitude (degs)    33.3567000

BASELINE(S):
Name      East      North      Up
NS        -37.116  -103.265  3.319
NW        -81.685  -28.214  3.106
SW        -44.566   75.049  -0.214

INSTRUMENT_PARAMETERS:
Visibility_Squared_Error    0.02000

WAVELENGTH_PARAMETERS:
Wavelength_Option          Spectrometer
Band_Lower_Limit           1.35
Band_Upper_Limit           1.95
Number_Of_Channels         1

OBSERVATION_PARAMETERS:
Hours_Before_Transit       -6.00
Hours_After_Transit        6.00
Minute_Increments         15.00

TARGET_MODEL_PARAMETERS:
Declination (degs)        +30.0
    
```

4.5.5 FITS Tab

The “FITS” tab (“Upload Image” mode only) provides an interface to view the contents of the uploaded FITS file that contains the arbitrary brightness image. Both the primary header and image itself can be viewed by selecting the appropriate sub-tab. The FITS Raw Image tab provides a contrast slider control. The displayed image is first “gamma corrected”, meaning the pixel values are raised to the power of 1/gamma; then it is scaled so that the smallest real pixel value corresponds to the smallest integer or byte value, and the largest real value corresponds to the largest integer or byte value.

The screenshot shows a software window with six tabs: Plot, Simulated Data, Instrument, FITS (selected), Image, and 2D Vis Modulus. The main area is titled "0. PRIMARY (IMAGE)" and has a sub-tab "RAWIMAGE". The text displayed is:

```

PRIMARY
Header  RAWIMAGE
SIMPLE  =                               T / Written by IDL:  Fri Aug 15 12:41:11 2008
BITPIX  =                               -64 / Number of bits per data pixel
NAXIS   =                               2 / Number of data axes
NAXIS1  =                               512 /
NAXIS2  =                               512 /
EXTEND  =                               T / FITS data may contain extensions
DATE    = '2008-08-15'                  / Creation UTC (CCCC-MM-DD) date of FITS header
COMMENT FITS (Flexible Image Transport System) format is defined in 'Astronomy
COMMENT and Astrophysics', volume 376, page 359; bibcode 2001A&A...376..359H
END
    
```


4.5.6 OI-FITS Tab

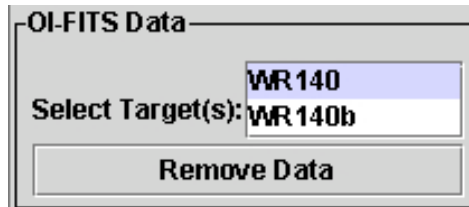
The “OI-FITS” tab (available in either mode but only when OI-FITS data exists) provides an interface to view the contents of a user uploaded OI-FITS file. All file extensions and tables are read in and a corresponding sub-tab is created to allow the user to view any extension of interest.

For a description of the OI-FITS format (an IAU standard) we refer the reader to:

http://www.mrao.cam.ac.uk/research/OAS/oi_data/oifits.htmlh

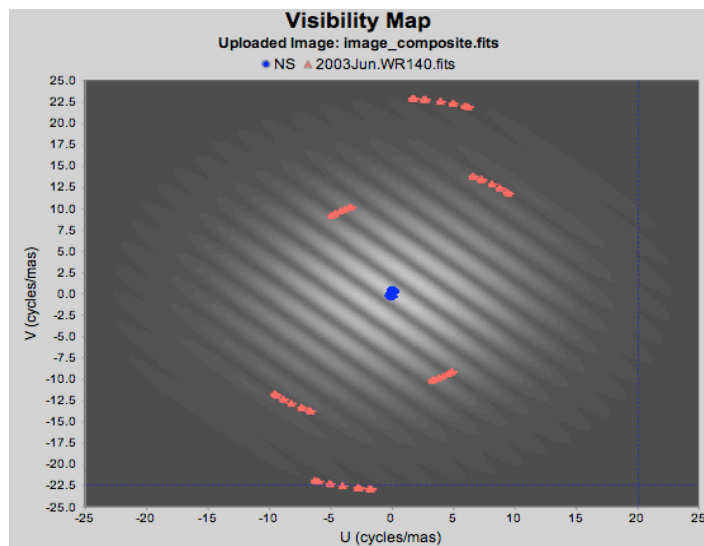
To read in an OI-FITS file, the operator selects “Read OI-FITS File” from the File pulldown menu. The visibility data (from the OI_VIS tables) and the visibility squared data (from the OI_VIS2 tables) are read in from all the tables within the file and associated with their respective target IDs as defined in the OI_TARGET table.

The “OI-FITS Data” sub-panel appears in the control panel allowing the user to select the data associated with one or more individual targets from the file. The targets in the list can be selected contiguously by clicking on the first desired target and while holding down the shift key, selecting the last target or individually by holding down the control key and clicking (which toggles the selection on and off) on the desired target.



The OI-FITS data are displayed in the plot (plot tab), together with the simulated data. Note that some observables listed in the “Plot Content Selection” X and Y Axis options may not exist or be derivable from the contents of the file uploaded (depending on which of the OI-FITS optional tables are present); those quantities will be disabled from the X and Y axis options in the “Plot Content Selection” menu.

In the Image Upload Mode, the u and v values of the data in the OI-FITS file are also overlaid on the visibility modulus image (in the 2D Vis Modulus tab), together with the u and v values of the simulated data.

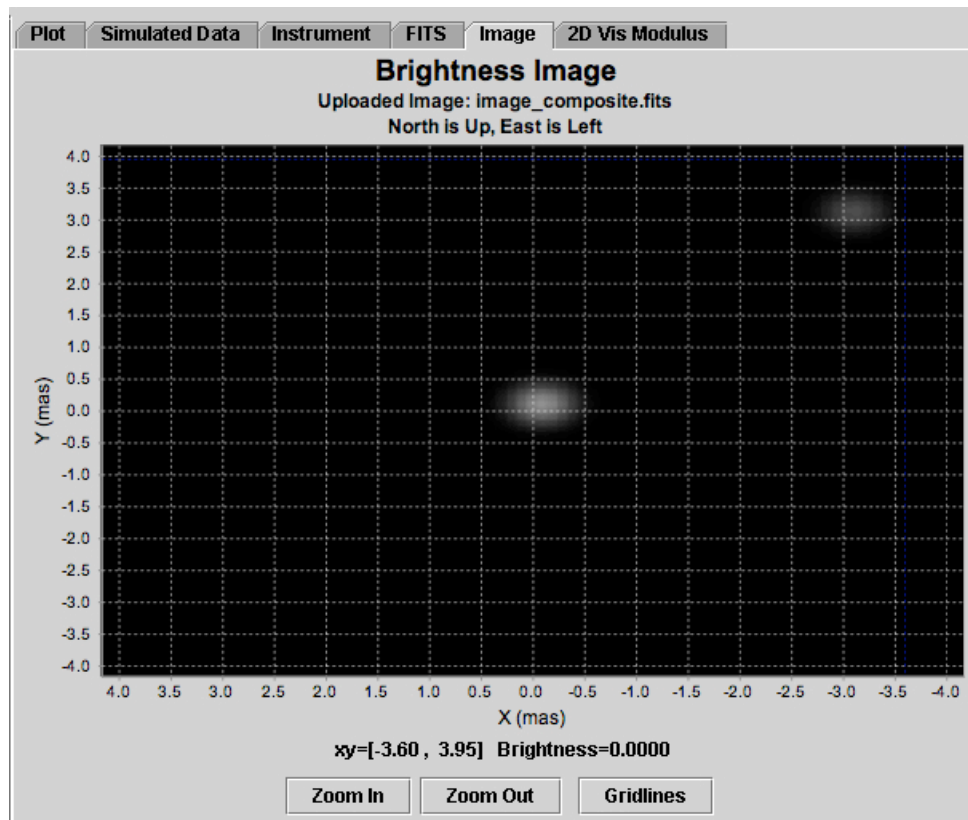


The “Remove Data” button removes the loaded OI-FITS data from the system. To reload the same data or a new OI-FITS data set, the user needs to re-select the “Read OI-FITS File” option from the File pull-down menu.

NOTE: The philosophy adopted by the VMT developers is that when the user has uploaded an OI-FITS file, the contents of all the VIS and VIS² are plotted along with the simulated data. No attempt is made to reconcile the parameters of a simulation with the contents of an OI-FITS file. Also, the VMT2 controls, e.g. wavelength selection or HA coverage, only act on the simulated data, and do not filter the OI-FITS data.

4.5.7 Image Tab

The “Image” tab (in “Upload Image” mode only) displays the uploaded brightness image. The tab displays “No Image Available” in image upload mode before an image has been uploaded or after an unsuccessful attempt to load an image (e.g. due to an incorrect FITS formatted file).



While over the displayed image, the mouse is tracked and its x-y coordinates and associated brightness value from the uploaded image are displayed at the bottom of the tab.

The “Zoom In” and “Zoom Out” buttons allow the user to zoom in and out respectively. When the limits of the Zoom In and Out features have been reached, the respective button becomes disabled.

The “Gridlines” button shows/hides gridlines overlaid at the labeled axes tick marks.

4.5.8 2D Vis Modulus Tab

The “2D Vis Modulus” tab (“Upload Image” mode only) displays the 2D visibility modulus for the uploaded image, along with the uv values of the simulated data. The tab displays “No Image Available” in “Upload Image” mode before an image has been uploaded or after an unsuccessful attempt to load an image (e.g. due to an incorrect FITS formatted file, FFT processing error, etc.).

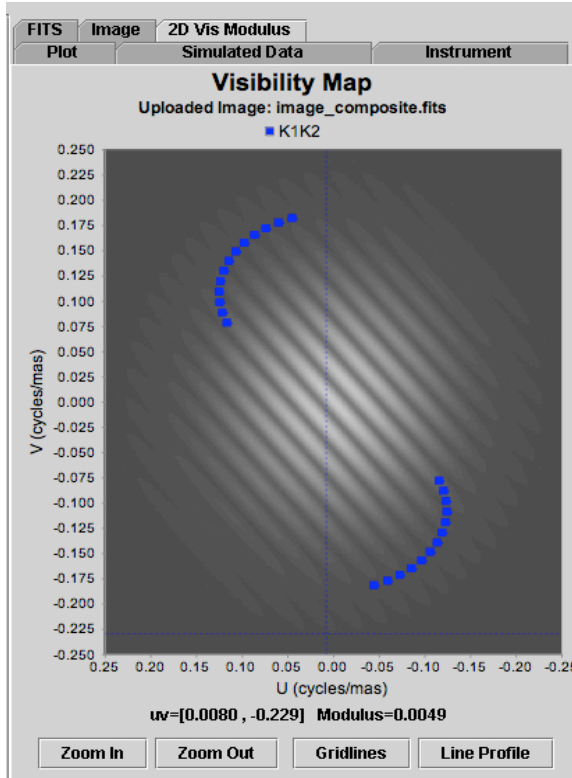


Figure 4.5.8 A – Visibility Map

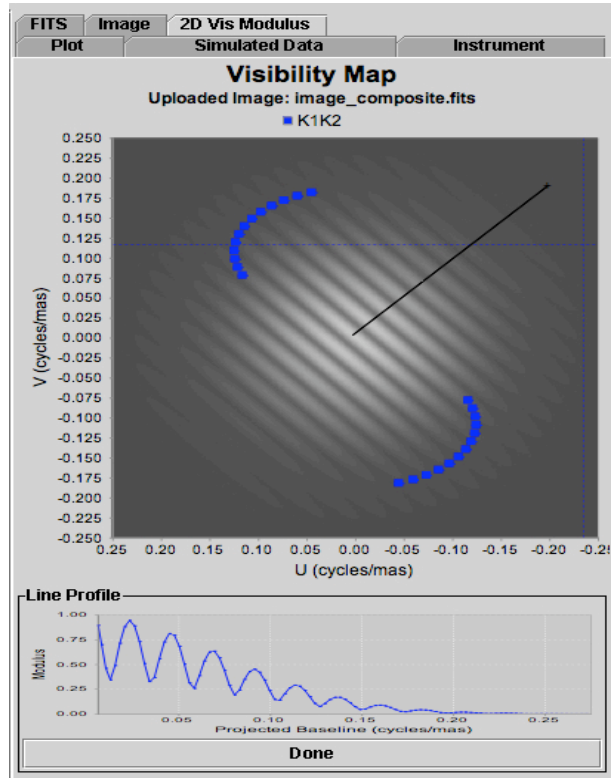


Figure 4.5.8 B – Visibility Map with Line Profile

While over the map, the mouse is tracked and its uv coordinates and associated visibility modulus value are displayed at the bottom of the tab (figure A – Visibility Map). When the mouse is clicked within the map image, the crosshairs “snap” to the closest simulated data uv point.

The “Zoom In” and “Zoom Out” buttons allow the user to zoom in and out respectively. When the limits of the Zoom In and Out features have been reached, the respective button becomes disabled.

The “Gridlines” button shows/hides gridlines overlaid at the labeled axes tick marks.

The “Line Profile” button allows the user to specify two points on the modulus map (via mouse clicks) and displays the profile in a two dimensional line plot (figure B – Visibility Map with Line Profile). The user can press the “Done” button to return to the previous panel.

4.5.9 Nuller Response Tab

The “Nuller Response Image” tab (“Upload Image” mode and only for the KI) displays the Nuller Beam Pattern with the same pixel scale as that entered by the user upon uploading their (FITS) brightness image. The tab displays “No Image Available” before an image has been uploaded or after an unsuccessful attempt to load an image (e.g. due to an incorrect FITS formatted file).

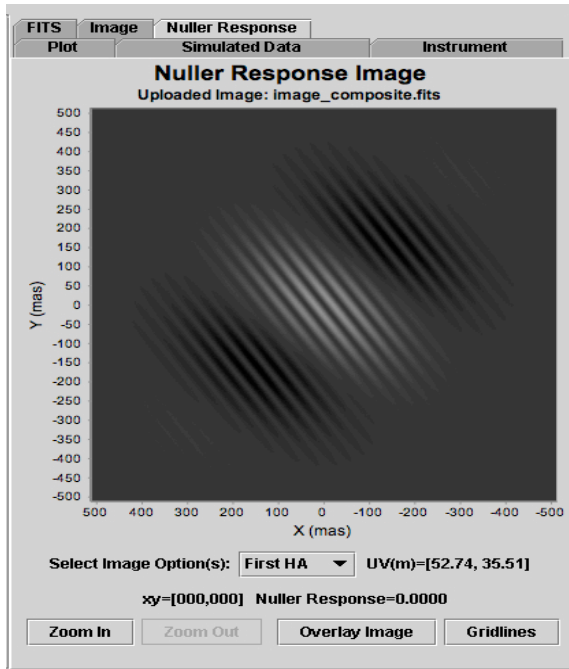


Figure 4.5.9 A – Beam Pattern

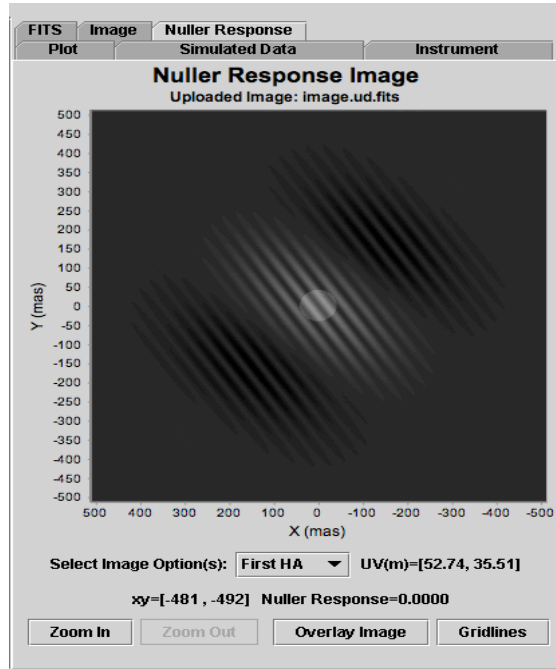


Figure 4.5.9 B – Beam Pattern with Overlaid Image

The user has the option to select the nuller beam pattern as calculated at the first, middle or last Hour Angle observation points. In spectrometer mode, the user also has the option of choosing the shortest, middle or longest wavelength.

The “Overlay Image” button allows the user to toggle between displaying the nuller response beam pattern only (Figure A - Beam Pattern) or also super imposing the uploaded brightness (Figure B - Beam Pattern with Overlaid Image).

While over the map, the mouse is tracked and it's x-y coordinates and associated Nuller Response value are shown at the bottom of the tab.

The “Zoom In” and “Zoom Out” buttons allow the user to zoom in and out, respectively. When the limits of the Zoom In and Out features have been reached, the respective button becomes disabled.

The “Gridlines” button shows/hides gridlines overlaid at the labeled axes tick marks.

5. Getting Help

For assistance with the VMT, you can:

- 1] reference our user's guide <http://nexsciweb.ipac.caltech.edu/vmt/vmtWeb/vmt-userguide.pdf>
- 2] email us at help@ipac.caltech.edu with "VMT" in the subject, or
- 3] visit our help desk: <http://nexsciweb.ipac.caltech.edu/cgi-bin/helpdesk/helpdesk.cgi>

A. File Formats

VMT Session File

Below is an example of the Target Model File that is used to save/load target models between sessions. The file has a .vmt extension.

```

VERSION                VMT_2.0
MODE                   1
IMAGE_UPLOAD_PARAMETERS 0.0976      1
/Users/VMT/Examples/example.fits
INTERFEROMETER        0           0
INSTRUMENT_PARAMETERS 0.0200      5.0E-4
WAVELENGTH_PARAMETERS 2           1.3500      1.9500      3
OBSERVATION_PARAMETERS -3.0000     3.0000     15.0000
TARGET_MODEL_PARAMETERS 45.0000
TARGET 0              1 UniformDisc-001    0.0000  0.0000  0.5000  12.0000  3.0000  2.0000
TARGET 1              3 Gaussian-002      10.0000 10.0000  0.3000  28.0000  3.5000  3.2500
TARGET 2              0 Point-003         0.5000  0.8000  0.1000
TARGET 3              2 Uniform-Ring-004    3.4000  1.7000  0.1000  43.0000  3.2500  2.7500  1.0000
OI-FITS_FILE
/Users/VMT/Examples/example.oifits
    
```

The definitions of the fields are:

```

MODE                [vmt_mode]

    Vmt mode:
        = 0 for Analytical Models Mode
        = 1 for Upload Image Mode
IMAGE_UPLOAD_PARAMETERS [Pixel Scale]
Image_Upload_File_Pathname
INTERFEROMETER         [Interferometer ID] [Selected Baseline IDs]
INSTRUMENT_PARAMETERS [Visibility Squared Error] [Null Depth Error]

WAVELENGTH_PARAMETERS [Wavelength Option] [Center Wavelength]
WAVELENGTH_PARAMETERS [Wavelength Option] [Band Lower Limit] [Band Upper Limit]
WAVELENGTH_PARAMETERS [Wavelength Option] [Band Lower Limit] [Band Upper Limit] [Channels]

    Wavelength Options:
        = 0 for Monochromatic Option
        = 1 for Broadband Option
        = 2 for Spectrometer Option

OBSERVATION_PARAMETERS [Hours Before Transit] [Hours After Transit] [Minute Increments]
TARGET_MODEL_PARAMETERS [Declination]
TARGET [Index][Type][Name][RAOffset][DecOffset][Flux][PA][OuterMajor][OuterMinor][InnerMajor]

    *For Point Source Targets: PA, OuterMajor, OuterMinor and Inner Major fields are not present
    *For Gaussian and Uniform Disc: Inner Major field is not present

OI-FITS_FILE
OI-FITS_File_Pathname
    
```

Prediction Data File

Below is an example of the ASCII text Prediction Data File that can be easily imported into other applications.

```
# Date/Time      : Mon Aug 18 15:29:11 PDT 2008
# Interferometer: KECK

# Target Model
# Declination : 0.0

# Image Upload Parameters
# Image Name   : No Image Uploaded
# Pixel Scale : 1.0
HrAngle  Baseline      U(m)      V(m)      Bp(m)     ZA(deg)   PA(deg)   V2(2.20)  N(2.20)
-3.00   K1K2          52.740   63.456   82.511    48.303    39.731    0.00000   1.00000
-2.75   K1K2          53.960   63.456   83.296    44.987    40.376    0.00000   1.00000
-2.50   K1K2          54.948   63.456   83.940    41.727    40.890    0.00000   1.00000
-2.25   K1K2          55.702   63.456   84.435    38.539    41.277    0.00000   1.00000
-2.00   K1K2          56.217   63.456   84.776    35.443    41.538    0.00000   1.00000
-1.75   K1K2          56.491   63.456   84.958    32.466    41.677    0.00000   1.00000
-1.50   K1K2          56.524   63.456   84.980    29.644    41.693    0.00000   1.00000
-1.25   K1K2          56.314   63.456   84.840    27.026    41.587    0.00000   1.00000
-1.00   K1K2          55.863   63.456   84.542    24.678    41.359    0.00000   1.00000
-0.75   K1K2          55.173   63.456   84.088    22.684    41.006    0.00000   1.00000
-0.50   K1K2          54.247   63.456   83.483    21.144    40.526    0.00000   1.00000
-0.25   K1K2          53.088   63.456   82.735    20.164    39.916    0.00000   1.00000
 0.00   K1K2          51.702   63.456   81.852    19.827    39.172    0.00000   1.00000
 0.25   K1K2          50.095   63.456   80.846    20.164    38.289    0.00000   1.00000
 0.50   K1K2          48.273   63.456   79.730    21.144    37.262    0.00000   1.00000
 0.75   K1K2          46.245   63.456   78.519    22.684    36.083    0.00000   1.00000
 1.00   K1K2          44.018   63.456   77.228    24.678    34.748    0.00000   1.00000
 1.25   K1K2          41.603   63.456   75.878    27.026    33.250    0.00000   1.00000
 1.50   K1K2          39.010   63.456   74.488    29.644    31.581    0.00000   1.00000
 1.75   K1K2          36.250   63.456   73.080    32.466    29.737    0.00000   1.00000
 2.00   K1K2          33.334   63.456   71.678    35.443    27.714    0.00000   1.00000
 2.25   K1K2          30.276   63.456   70.308    38.539    25.507    0.00000   1.00000
 2.50   K1K2          27.088   63.456   68.996    41.727    23.117    0.00000   1.00000
 2.75   K1K2          23.784   63.456   67.767    44.987    20.547    0.00000   1.00000
 3.00   K1K2          20.378   63.456   66.648    48.303    17.804    0.00000   1.00000
```

B. Algorithms

B.1. Spatial frequencies (u,v)

We use the baseline coordinates: Bup, Beast and Bnorth, to:

1) compute baseline in "XYZ" reference frame:

$$X = B_u * \cos(l) - B_n * \sin(l)$$

$$Y = B_e$$

$$Z = B_u * \sin(l) + B_n * \cos(l)$$

Where:

l is the site latitude in radians (*pi/180 to convert from degrees). XYZ will be in meters.

2) compute u,v:

$$u = X * \sin(ha) + Y * \cos(ha)$$

$$v = -X * \sin(d) * \cos(ha) + Y * \sin(d) * \sin(ha) + Z * \cos(d)$$

where:

ha = hour angle in radians (*15.*pi/180 to convert from hours).

d = target declination in radians (*pi/180 to convert from degrees).

So u,v will be in meters too.

The baseline coordinates [East, North, Up] currently used by the VMT are:
(please let us know if your interferometer's baselines need to be updated!)

PTI: Latitude => +33.3567
 PTI_NS => [-37.116352,-103.264746,3.319338]
 PTI_NW => [-81.685124,-28.214086,3.105647]
 PTI_SW => [-44.566402,75.048984,-0.214424]

KI: Latitude => 19.826667
 KI_K1K2 => [51.702317,67.455618,-0.003674]

NPOI: Latitude => +35.1933
 NPOI_AN0AC0 => [-0.1400,22.8500,0.0000]
 NPOI_AN0AE0 => [-17.6300,30.0900,0.0000]
 NPOI_AN0AW0 => [19.7500,32.7100,0.0000]
 NPOI_AC0AE0 => [-17.4900,7.2400,0.0000]
 NPOI_AC0AW0 => [19.8900,9.8600,0.0000]
 NPOI_AE0AW0 => [37.3800,2.6200,0.0000]

NPOI_AN0N00 => [-1.8300,16.5100,0.0000]
NPOI_AN0N01 => [-1.580,14.300,0.000]
NPOI_AC0N00 => [-1.690,-6.340,0.000]
NPOI_AC0N01 => [-1.440,-8.550,0.000]
NPOI_AE0N00 => [15.800,-13.580,0.000]
NPOI_AE0N01 => [16.050,-15.790,0.000]
NPOI_AW0N00 => [-21.580,-16.200,0.000]
NPOI_AW0N01 => [-21.330,-18.410,0.000]
NPOI_N00N01 => [0.250,-2.210,0.000]

CHARA: Latitude => +34.224383
CHARA_W2S1 => [-69.659,199.152,0.470]
CHARA_W2S2 => [-63.911,165.571,-0.174]
CHARA_W2E1 => [-195.001,-106.784,6.375]
CHARA_W2E2 => [-140.060,-70.565,3.258]
CHARA_W2W1 => [105.409,-17.170,11.298]
CHARA_W1S1 => [-175.069,216.322,-10.828]
CHARA_W1S2 => [-169.320,182.741,-11.472]
CHARA_W1E1 => [-300.410,-89.614,-4.923]
CHARA_W1E2 => [-245.469,-53.395,-8.040]
CHARA_E2S1 => [70.401,269.717,-2.788]
CHARA_E2S2 => [76.149,236.135,-3.432]
CHARA_E2E1 => [-54.941,-36.219,3.117]
CHARA_E1S1 => [125.342,305.936,-5.905]
CHARA_E1S2 => [131.090,272.354,-6.549]
CHARA_S2S1 => [-5.748,33.581,0.644]

VLTl: Latitude => -24.6233
VLTl_U1U2 => [24.31,51.08,0,0]
VLTl_U1U3 => [53.97,87.08,0,0]
VLTl_U1U4 => [112.59,65.45,0,0]
VLTl_U2U3 => [29.66,36.00,0,0]
VLTl_U2U4 => [88.28,14.37,0,0]
VLTl_U3U4 => [56.62,-21.63,0,0]

SUSI: Latitude => -30.3223
SUSI_N1S1 => [0, -5.0, 0]
SUSI_N1S2 => [0, -10.0, 0]
SUSI_N3S1 => [0, -15.0, 0]
SUSI_N3S2 => [0, -20.0, 0]
SUSI_N1S3 => [0, -30.0, 0]
SUSI_N3S3 => [0, -40.0, 0]
SUSI_N4S1 => [0, -55.0, 0]
SUSI_N4S3 => [0, -80.0, 0]
SUSI_N1S4 => [0,-110.0, 0]
SUSI_N4S4 => [0,-160.0, 0]

B.2. Visibility Equations – Analytical Models

Approximations: In this release we base our calculations on the van Cittert-Zernike theorem, which relates the complex visibility to the brightness distribution on the sky by a two-dimensional Fourier transform, representing each telescope by a delta-function (i.e. we do not consider the actual antenna pattern of each telescope), and neglecting other apodizing functions such as those produced by coupling into single-mode fibers, often used to clean up the incoming wavefronts.

The elementary morphologies used in this release are intended to represent 2D surface brightness on the sky. Their visibility functions are therefore also 2D. Moreover, the elementary components need not be circularly symmetric; they can be elliptical and with any orientation on the sky (some astronomical objects are approximately elliptical on the sky, such as the disk of a fast rotating star, while other objects, such as a uniform disk, appear elliptical when they are inclined to the line of sight).

The formulae below are based on the following properties: (1) any circularly symmetric brightness has a Fourier transform (visibility) that depends on only one variable, sometimes referred to as the "fringe spacing": $s = \sqrt{u^2 + v^2} / \text{wavelength}$; (2) the ellipticity (uniform or Gaussian) can be taken into account by a coordinate transformation starting from the formulae for symmetric brightness, with the result that the same formulae can be used provided we replace s by:

$$s' = s'(u, v; \phi, a, b) = s \cdot \sqrt{\cos^2(\theta - \phi) + (b/a)^2 \sin^2(\theta - \phi)}$$

where:

$$s = \sqrt{u^2 + v^2} / \text{wavelength}$$

θ = baseline position angle = $\text{atan}(u/v)$; measured East of North.

a = angular dimension of ellipse major axis.

b = angular dimension of ellipse minor axis.

ϕ = ellipse major axis position angle, measured East of North.

u and v are the components of the projected baseline vector (in meters) . The wavelength of observation must be in same units as u and v (meters).

Note: the elliptical brightness can be thought of as resulting from tilting a circularly symmetric brightness by angle i , such that $\cos(i) = b/a$. $i = 0^\circ$ recovers the face-on morphology.

The user is also allowed to place each component anywhere on the sky by specifying right ascension and declination coordinate offsets X_0 and Y_0 with respect to the center. Optical interferometers usually track a bright compact object located at this phase center ($X_0=0, Y_0=0$). If we call $V(s')$ the visibility function for one of the basic components, then (by the shifting property of the Fourier transform) the coordinate offsets simply introduce the (complex) multiplicative factor: $\exp(-2\pi i (X_0 u + Y_0 v))$. The ability to place any number of elementary models arbitrarily on a map will allow the user to better approximate the morphology of an object of interest as a composite model. Each model component is specified to contribute a fraction (f) of the total flux in the composite object. When composing their source models, users must be mindful that interferometers have field of view limitations.

Below we give the monochromatic analytical expressions for the elementary complex visibilities:

(The parameters of sky locations and angular sizes X_0, Y_0, a, b , and ϕ are internally converted from the user input units to radians).

Point Source

Inputs:

f: flux fraction (of total) (dimensionless)
 X_0, Y_0 offsets (input in mas)

$$V(s') = V(s) = V(u, v; f, X_0, Y_0) = f * \exp(-2 * \pi * i * (X_0 * u / \text{wavelength} + Y_0 * v / \text{wavelength}))$$

Uniform Disk

Inputs:

f: flux fraction (dimensionless)
 X_0, Y_0 offsets (mas)
 a: angular diameter along major axis (mas)
 b: angular diameter along minor axis (mas)
 ϕ : position angle of ellipse major axis, East of North (degrees)

$$V(s') = V(u, v; \phi, a, b, f, X_0, Y_0) = f * 2 * J_1(\pi * a * s') / (\pi * a * s') * \exp(-2 * \pi * i * (X_0 * u / \text{wavelength} + Y_0 * v / \text{wavelength}))$$

where J_1 is the 1st order Bessel function.

Gaussian

Inputs:

f: flux fraction (dimensionless)
 X_0, Y_0 offsets (mas)
 a: angular diameter along major axis (mas) (FWHM)
 b: angular diameter along minor axis (mas) (FWHM)
 ϕ : position angle of ellipse major axis, East of North (degrees)

$$V(s') = V(u, v; \phi, a, b, f, X_0, Y_0) = f * \exp[-(\pi^2 * a^2 * s'^2) / (4 * \ln(2))] * \exp(-2 * \pi * i * (X_0 * u / \text{wavelength} + Y_0 * v / \text{wavelength}))$$

where \ln is the natural logarithm.

Uniform Ring

Inputs:

f: flux fraction (dimensionless)
 X_0, Y_0 offsets (mas)
 a_1 : angular inner ring diameter along major axis (mas)

b1: angular inner ring diameter along minor axis (mas)
 a2: angular outer ring diameter along major axis (mas)
 phi: position angle of ellipses major axis, East of North (degrees)

$$V(s') = V(u,v;\phi,a1,b1,a2,f,X0,Y0) = \\ = f * [a2/2 * J1(\pi*a2*s')/s' - a1/2 * J1(\pi*a1*s')/s'] / (\pi/4 * (a2^2 - a1^2)) * \\ * \exp(-2*\pi*i*(X0*u/wavelength + Y0*v/wavelength))$$

Note: as before, s' accounts for the ellipticity through the aspect ratio $(b1/a1)=(b2/a2)$; hence only $b1$ or $b2$ is required as an input parameter, but not both.

Visibility for the Composite Model

If we call $V(s')_i$ the normalized visibility function for each (possibly offset) basic component as given above, the final (complex) visibility will be:

$$V(s') = \text{Sum}[V(s')_i]$$

Finally, the visibility modulus (squared) equals the product of the above complex visibility and its complex conjugate:

$$|V(s')|^2 = V(s') * V^*(s')$$

or equivalently:

$$|V(s')|^2 = \text{Re}(V)^2 + \text{Im}(V)^2$$

where Re and Im denote the real and imaginary parts of the complex visibility.

KI Null

Ignoring details of the KIN beam pattern on the sky (specifically, due to (1) the half-circle shapes of the K1 and K2 pupils that produce the long baseline fringes, and (2) the short-baseline cross-fringes used for thermal background modulation), the null depth may be approximated as:

$$N = (1 - |V|)/(1 + |V|)$$

where $|V|$ is the visibility modulus for a single-component or composite model, computed as described above. The above formula is a good approximation provided the short baselines (~5 m, or ~400 mas fringe spacing) do not significantly resolve any component of the object's brightness distribution.

B.3. Numerical Algorithms – Image Upload

B.3.a. Visibility

Visibility modulus (and visibility squared) is computed from a 2D FFT of the user input image. Bilinear interpolation is used to obtain the visibility at the uv points that correspond to the user's selection of an interferometer/baseline(s) and HA coverage.

In the current version, the VMT is limited to images of at most 512x512 pixels in size, unless the JVM memory is increased by the user as describe in Section 3 of this manual.

An important consideration for the accuracy of the FFT-based results is that of zero-padding. Users are advised to create images that contain their brightness region of interest surrounded by an area ~ 4 as big filled with zeroes, in order to be immune to the effects on the FFT of the square-shaped support for the image.

The uploaded images are assumed to be monochromatic, computed at the wavelength entered by the user in the Wavelength Parameters Panel.

As is also the case for the calculations of the Analytical Mode, broadband and spectrometer calculations only reflect the effects of wavelength on the spatial frequencies u and v , and not any wavelength dependence of the brightness itself. In that sense, the broadband and spectrometer calculations will be strictly correct only for grey emission.

As was described earlier, the VMT always displays the uploaded images and 2D visibility maps with North=Up and East=Left, following standard convention in astronomy. The input image is by default assumed to be oriented East=Left. However, the user can flip the input image left-to-right from within the tool via a checkbox in the Preferences tab.

B.3.b. KI Nuller

In Image Upload mode, the KI Null Depth calculation includes, in addition to the long baseline Keck-Keck fringes, two additional terms of the KI Nuller beam pattern: the projection on the sky of the split-aperture pupils of each Keck, and the wide (a.k.a. "cross-combiner") fringes formed using the two halves of each Keck (which are used for signal modulation in the presence of the strong infrared thermal background).

Therefore, the KI Nuller beam pattern is the product of three images:

$T(x,y)$: the single telescope patterns.

$B_{xc}(x,y)$: short baseline fringes.

$B_{long_peak}(x,y)$ or $B_{long_null}(x,y)$: long baseline fringes at peak or at null.

Where (x,y) represent angular sky coordinates. The peak and null signals are computed by multiplying, pixel by pixel, the appropriate product of three beam pattern images by the user uploaded input brightness image $I(x,y)$:

- $Peak_signal = \text{Sum}_{x,y}[I(x,y) * T(x,y) * B_{xc}(x,y) * B_{long_peak}(x,y)]$
- $Null_signal = \text{Sum}_{x,y}[I(x,y) * T(x,y) * B_{xc}(x,y) * B_{long_null}(x,y)]$

Finally, the normalized null depth, or leak, is computed as the ratio of the null to peak signals:

- $\text{Null_Depth} = \text{Null_signal}/\text{Peak_signal}$

As described above for the visibility calculations, broadband and spectrometer null depth calculations only reflect the effects of wavelength on the spatial frequencies u and v , and not any wavelength dependence of the brightness itself. In that sense, the broadband and spectrometer calculations will be strictly correct only for grey emission.

Each of the KI Nuller beam pattern terms is computed as follows:

Telescope pattern:

The PSF that correspond to each Keck's half-pupils can be modeled as an elliptical Gaussian, with minor axis always pointing to toward zenith:

$$T(x,y) = \exp(-0.5 * z)$$

with:

$$\begin{aligned} z &= (xr/\sigma_{\text{major}})^2 + (yr/\sigma_{\text{minor}})^2 \\ xr &= x * \cos(\theta) - y * \sin(\theta) \\ yr &= x * \sin(\theta) + y * \cos(\theta) \\ \sigma_{\text{major}} &= \text{fwhm}_{\text{major}} / (2 * \sqrt{2 * \log(2)}) \\ \sigma_{\text{minor}} &= \text{fwhm}_{\text{minor}} / (2 * \sqrt{2 * \log(2)}) \\ \text{fwhm}_{\text{major}} &= 0.45 \text{ arcsec} \\ \text{fwhm}_{\text{minor}} &= 0.31 \text{ arcsec} \end{aligned}$$

The angle θ determines the orientation of the elliptical Gaussian on the sky as a function of H.A., as described below.

Cross-combiner fringes:

The short baseline fringes formed by interfering the half-pupils of each Keck have a constant ~4m baseline (because each telescope tracks the object), hence:

$$B_{\text{xc}}(x,y) = \cos(2 * \pi * (x * u_{\text{xc}} + y * v_{\text{xc}}) / \text{wavelength})$$

Where u_{xc} and v_{xc} are the East and North components of the short baseline (in meters), which also must take into account the image rotation, as described below. Note that the telescope pattern and cross-combiner fringes rotate together, but their orientation with respect to the long baseline fringes varies as a function of H.A.

Long baseline fringes

At peak:

$$B_{\text{long_peak}}(x,y) = 1 + \cos(2 * \pi * (x * u + y * v) / \text{wavelength})$$

At null:

$$B_long_null(x,y) = 1 - \cos(2 \cdot \pi \cdot (x \cdot u + y \cdot v) / \text{wavelength})$$

where u and v are the East and North components of the Keck-Keck baseline (in meters).

Image rotation

The Keck telescopes have alt-az mounts. An image rotator keeps the split-pupils fixed on the Adaptive Optics wavefront sensor. Hence the PSF and cross-combiner (short baseline) fringes rotate together as a function of H.A., with the elliptical single telescope pattern minor axis always pointing toward zenith. The orientation of the long baseline fringes inside this ellipse is given by the u and v components of the Keck-Keck baseline. The orientation of the PSF and cross-combiner fringes is given by the following equations (many thanks to Mark Kuchner):

Length of cross-combiner baseline (m):

$$Bxc_length = 4.$$

PA of cross-combiner baseline (deg):

$$PA_xc = 90.0$$

sin and cos of position angle of mirror:

$$\sin PA = \sin(\text{azimuth}) \cdot \cos(\text{latitude})$$

$$\cos PA = \sqrt{1.0 - \sin PA^2}$$

cross-combiner baseline component if the short baseline were at PA=0 on the mirror (vertical when the altitude is zero):

$$uvert = Bxc_length \cdot \sin PA$$

$$vvert = Bxc_length \cdot \cos PA$$

rotate to take into account the actual orientation of baseline on the mirror:

$$uxc = \cos(PA_xc) \cdot uvert + \sin(PA_xc) \cdot vvert$$

$$vxc = -\sin(PA_xc) \cdot uvert + \cos(PA_xc) \cdot vvert$$

and the angle theta above in the rotation of the elliptical telescope pattern is:

$$\text{theta (deg)} = \text{atan}(uxc/vxc) \cdot 180/\pi + 270.$$

C. Acronyms / Glossary

Bp	Projected Baseline Length
CHARA	Center for High Angular Resolution Array
Dec	Declination
degs	Degrees
FFT	Fast Fourier Transform
FITS	Flexible Image Transport System
GUI	Graphical User Interface
HA	Hour Angle
JAR	Java Archive File
JDK	Java Development Kit
JRE	Java Runtime Environment
KI	Keck Interferometer
mas	milliarcseconds
$M\lambda$	millions of wavelengths
MID	mid-infrared
MSC	Michelson Science Center
ND	Null Depth a.k.a. Leakage
NExSci	NASA Exoplanet Science Institute (formerly MSC)
NPOI	Navy Prototype Optical Interferometer
OI-FITS	Optical Interferometry FITS
PA	Position Angle
PSF	Point Spread Function
PTI	Palomar Testbed Interferometer
RA	Right Ascension
SUSI	Sydney University Spatial Interferometer
TBD	To Be Determined
TBS	To Be Supplied
UD	Uniform Disc
UR	Uniform Ring
V^2	Visibility Squared
V	Visibility modulus
VMT	Visibility Modeling Tool
VLTI	Very Large Telescope Interferometer
ZA	Zenith angle

D. Acknowledgements

We would like to acknowledge the following individuals for their help testing the VMT, for providing code snippets, and valuable discussions: Jean-Philippe Berger, Theo ten Brummelaar, Dawn Gelino, Kaspar von Braun, Rachel Akeson, David Ciardi, Andy Boden, Babar Ali, Valeri Makarov, Gerard van Belle, Wes Traub, Mark Colavita, Gene Serabyn, Mark Kuchner, John Monnier, Claude Felizardo, Mark Abajian, Heidi Brandenburg, Stephanie Leifer, and Nathan Sutter.