September 20, 2007

MOSFIRE AUTOMATIC SLIT CONFIGURATION GENERATOR

Christopher R. Klein[1]
Advisor: Charles C. Steidel

ABSTRACT

The Multi-Object Spectrometer For Infra-Red Exploration (MOSFIRE) is a new instrument intended for the Keck I Cassegrain focus that will allow for many more spectrographic observations per night than current instruments. This multiplex advantage of up to 46 slits is achieved by using a cryogenic Configurable Slit Unit, or CSU, that will be reconfigurable under remote control in less than 5 minutes. The MOSFIRE Automatic Slit Configuration Generator (Mascgen) computer program has been written to aid observers in the designing and optimization of slit configurations. Given an input object list with prioritized objects, user-defined CSU and slit constraints, and desired iteration parameters, Mascgen will compute the near-optimum slit configuration to maximize total priority.

Subject headings: instrumentation: spectrographs

1. INTRODUCTION

The Multi-Object Spectrometer For Infra-Red Exploration (MOSFIRE) is a new instrument intended for the Keck I Cassegrain focus that will allow for many more spectrographic observations per night than current instruments. This multiplex advantage of up to 46 slits is achieved by using a cryogenic Configurable Slit Unit, or CSU, that will be reconfigurable under remote control in less than 5 minutes. The optical design of MOSFIRE provides near-IR ($\sim$0.97–2.45 μm) multi-object spectroscopy over a 6.13'$\times$6.13' field of view (FOV) with a resolving power of R$\sim$3,270 for a 0.7" slit width (2.9 pixels in the dispersion direction), or imaging over a FOV of 6.14' with 0.18" per pixel sampling. The slits in the CSU are formed by moving opposable bars from both sides of the focal plane. An individual slit has a length of about 7", but bar positions can be aligned to make longer slits. When the bars are removed to their full extent and the grating is changed to a mirror, MOSFIRE becomes a wide-field imager. Using a single 2K$\times$2K H2-RG HgCdTe array with exceptionally low dark current and low noise, MOSFIRE will be extremely sensitive and ideal for a wide range of science applications.

One of the primary motivations for MOSFIRE's creation was to increase infrared spectroscopic observing efficiency. Current multi-object spectrometers, such as Keck's Low Resolution Imaging Spectrometer (LRIS), use milled aluminum slit masks to form multiple slits of varying width, length, and position in the focal plane. These masks must be designed and milled before the night's observing and, like the rest of the instrument, they must be cooled with liquid nitrogen. LRIS uses a carriage of up to eight slit masks to allow for observations with different fields of view and/or different slit configurations to be made in the same night. MOSFIRE is an improvement over this design because it allows for on-the-fly slit mask reconfiguration and removes the necessity of preparing aluminum slit masks in advance. To reconfigure the slits the observer simply uploads a list of bar positions representing the new slit configuration to the CSU Server.

[1] Caltech, Astronomy Department, Pasadena, CA 91125; cklein@caltech.edu

The MOSFIRE Automatic Slit Configuration Generator (Mascgen) will help observers to create optimum slit configurations. Mascgen is written in Java to enable cross-platform compatibility and it was developed with Java Runtime Environment (JRE) 1.5. When provided with a prioritized input object list and other user-defined parameters, Mascgen will find the near-optimum slit configuration and produce the corresponding slit list, bar positions list, and SAOImage Ds9 region file.

2. USER INTERFACE

There are both command line and graphical user interface (GUI) versions of Mascgen and, while the underlying optimization routines are the same, this paper focuses on the stand alone GUI version. The command line version was designed specifically for implementation in MSCGUI, the MOSFIRE Slit Control Graphical User Interface. It is technically possible to operate the command line version outside of MSCGUI, but this is discouraged due to the numerous arguments that must be specified in the command line program execution call. Additionally, the GUI version can be run multiple times without exiting the program and it remembers the last used set of input parameters.

The main Mascgen window is the interface used to point Mascgen to the correct input object list and to define various other input parameters (see Figure 1). An in-depth discussion and explanation of these inputs follows in the next two sections.

Once the inputs are made in the main window, the user selects to run Mascgen normally by clicking the "Run" button or to run Mascgen with the option of using the center of priority (CoP) as the initial CSU center position by clicking the "Run with CoP" button. Mascgen then generates the Run Progress or Run with CoP Progress window to display feedback on the progression of the optimization execution. Figure 2 shows an example Run with CoP Progress window. Before the optimizing iteration loop is initiated, this window displays the total number of iterations to be performed. Each time Mascgen finds a new best slit configuration it reports the iteration number and total priority. After the optimization iteration loop is completed, Mascgen reports the total priority, number

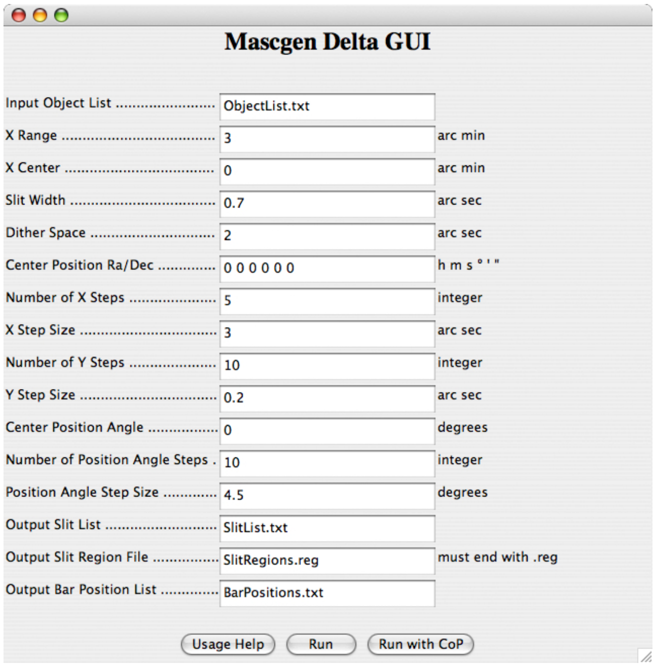

FIG. 1.— Mascgen Graphical User Interface as viewed with Mac OS X.

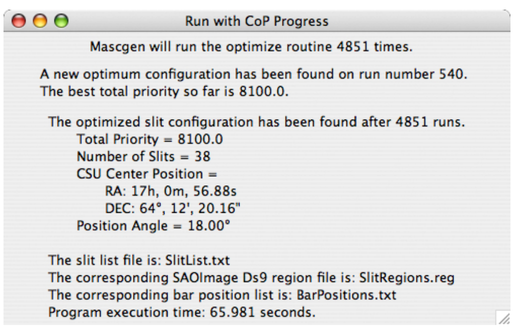

FIG. 2.— Mascgen Run with CoP Progress window as viewed with Mac OS X.

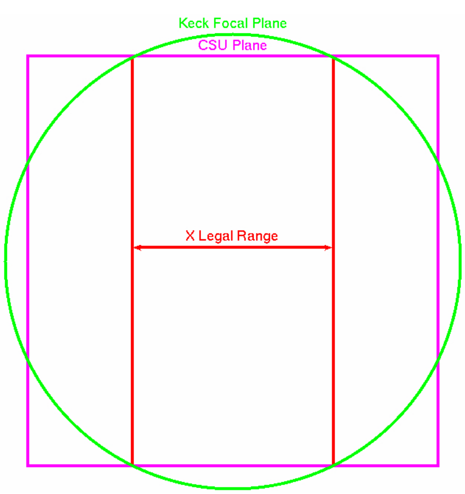

FIG. 3.— CSU Plane with circular Keck Focal Plane and 3'-wide X Legal Range.

of slits, center position, and position angle of the best slit configuration found during the iteration loop. It also reports the names of the three output files and the total program execution time.

3. CSU DIMENSIONS

The cryogenic Configurable Slit Unit is a square of length 266.8 mm. The conversion from CSU mm to arc seconds is 1 mm = 1.37896", thus the CSU Plane width and height is 367.907". The height of a single slit is 7.033" and the total bar overlap between two slits is 0.965". The Keck I Cassegrain Focal Plane is taken to be a circle of radius 3.4' = 204", which means that the corners of the CSU Plane are cut off by the circle. Mascgen properly accounts for this and will not assign slits to objects outside of the circular focal plane. Additionally, before executing an optimization run the user specifies the width and horizontal position of the X Legal Range. The X Legal Range is used to control spectral coverage on the detector by giving the user adjustable limits on the horizontal positions of slits.

Figure 3 shows the relative dimensions of the Keck Focal Plane, the CSU Plane, and an X Legal Range of width 3'. Mascgen will only assign slits to objects located within the Keck Focal Plane, the CSU Plane, and the X Legal Range.

The bars are tilted by 4° with respect to the CSU and detector, and consequently, the slits are also tilted. In order for Mascgen to ensure that the object falls in the horizontal center of its slit even when the object may be displaced vertically from the center, the program adjusts the overall horizontal position of the slit.

4. INPUT OBJECT LIST

The main Mascgen input is the input object list (in the form of a text file). The object list has one row for each object and each row consists of 13 columns or entries separated by white space. The columns are object name, scientific priority, magnitude, right ascension (RA) hours, RA minutes, RA seconds, declination (Dec) degrees, Dec minutes, Dec seconds, epoch, equinox, junk 1, and junk 2[1]. This common object list format was selected to be supported by Mascgen mainly because it is also used by Slitassign, a similar program written for LRIS. Technically, Mascgen does not use the magnitude, epoch, equinox, junk 1, and junk 2 data. It is important that the 13 column format be maintained, but otherwise Mascgen ignores these values.

Table 1 is an example of the object list format. Note that the actual text file should not contain the header column labels. Mascgen does all computations to double floating point precision (about 16 decimal digits). This means that the priority[2], RA seconds, and Dec seconds can all be supplied with any reasonably desired level of precision. Of course, the Ra hours, Ra minutes, Dec degrees, and Dec minutes must be given as whole numbers and conform to valid boundaries, i.e., Ra hours cannot be negative or greater than 23, etc.

[1] Junk 1 may also be known as RA proper motion and junk 2 may also be Dec proper motion.

[2] Priorities should be positive and can be decimals, but negative priorities should not be used. The scale of priorities should be linear (i.e., an object with priority 100 should be twice as important as an object with priority 50) and, although not necessary, one should avoid assigning the same priority value to two different objects.

TABLE 1 Input Object List Example

Obj Name	Priority	Mag	RA Hours	RA Min	RA Sec	Dec Deg	Dec Min	Dec Sec	Epoch	Equinox	Junk 1	Junk 2
M56	237	9.50	19	16	37.68	30	11	8.76	2000	2000	0	0
M57	785	9.50	18	53	35.10	33	1	41.34	2000	2000	0	0
M58	1129	11.0	12	37	43.80	11	49	5.46	2000	2000	0	0

5. OTHER INPUT PARAMETERS AND OUTPUT FILES

As shown in Figure 1, Mascgen has 16 separate input parameters. This section will explain the inputs, their formatting, and the output files Mascgen produces.

Input Object List: full name of the text file containing the input object list. If there is an error in this file, Mascgen will not run properly. Note that Mascgen only has access to files within the directory or folder containing the program.

X Range: horizontal size in arc minutes of the X Legal Range. The X Range parameter cannot be $\leqslant$ 0' and it cannot be > CSU width, 6.132'. If an invalid X Range is given, the default value of 3' is used.

X Center: horizontal position in arc minutes of the X Legal Range. 0' is the center of the CSU, with negative extending left and positive extending right. In order for the X Legal Range to fall within the the CSU Plane, the X Center parameter cannot be $\leqslant$ -3.066' or $\geqslant$ 3.066'. If an invalid X Center is given, the default value of 0' is used.

The X Legal Range allows the user the control the spectral coverage observed for all target objects. The spectrum of each object as recorded on the detector is projected to both the left and right of the slit, but the edge of the detector is at the edge of the CSU Plane. This could pose a problem, for example, if the slit fell on the far right of the CSU Plane and the most important spectral coverage was projected to the right of the slit. In this case, assigning a negative X Center with a small X Range will ensure that all slits are placed well to the left of the right edge.

Slit Width: standard slit width in arc seconds to be applied to all slits. The Slit Width parameter cannot be $\leqslant$ 0 or > CSU Width, 367.907". If an invalid Slit Width is given, the default value of 0.7" is used. The Slit Width value should be determined by the user and is usually affected by the seeing conditions at the telescope.

Dither Space: distance in arc seconds from the top and bottom of each slit to be reserved for dithering or nodding. The Dither Space parameter cannot be < 0" or > half the single slit height, 3.516". If an invalid Dither Space is given, the default value of 2" is used. Mascgen will not create slits with objects falling in the dither space.

Center Position Ra/Dec: starting center position of the CSU in the format RA hours, RA minutes, RA seconds, Dec degrees, Dec minutes, Dec seconds. Just like the object coordinates of the input object list, the center position coordinates must be physically valid and only RA seconds and Dec seconds can be given as decimals. The individual values must be separated by a blank space. For example, the position generally written as 19h 16m 37.68s, 30° 11' 8.76" (or as 19:16:37.68, +30:11:8.76) should be entered as 19 16 37.68 30 11 8.76. If the declination is negative, make sure to include a minus in front of the value for Dec degrees. A plus sign indicates positive and values without a plus or minus are taken as positive.

Number of X Steps: number of iterative steps to be performed in the x dimension. This parameter must be a whole number $\geqslant$ 0. The Number of X Steps parameter is not the absolute number of iterations performed along the x dimension. Instead, it is the number of steps taken below or above the center position. So, the actual number of steps is Number of X Steps $\times$ 2 + 1. For example, if the Number of X Steps was 3, the actual number of iterations would be 7; 3 below the center, 1 at the center, and then 3 above the center. This same scheme applies to the Number of Y Steps and the Number of Position Angle Steps. Employing this scheme ensures that, regardless of the number of steps or the step size for any of the dimensions, the CSU center position as given by the Center Position Ra/Dec parameter will always be one of the iteration steps.

X Step Size: length in arc seconds between iterative steps in the x dimension. This value can be a decimal and should be positive. If a negative value is used, Mascgen will still perform properly, but the iterations are run "backwards".

Number of Y Steps: number of iterative steps to be performed in the y dimension. Analogous to the Number of X Steps parameter for steps in the y direction.

Y Step Size: length in arc seconds between iterative steps in the y dimension. Analogous to the X Step Size parameter for steps in the y direction.

Center Position Angle: angle (in degrees) at which the CSU Plane is rotated with respect to the sky at the given Center Position Ra/Dec. Positive is counter-clockwise (when looking out through the CSU towards the sky).

Number of Position Angle Steps: number of iterative steps to be performed in the position angle dimension. Analogous to the Number of X Steps parameter for steps in position angle.

Position Angle Step Size: angle in degrees between iterative steps in the position angle dimension. Analogous to the X Step Size parameter for steps in position angle.

Output Slit List: full name of the text file Mascgen will create to store the list of slits. Each row of the file has 18 columns. They are slit number, slit center position Ra/Dec (six columns), slit width in arc seconds, slit length in arc seconds, corresponding object name, object priority, object vertical displacement from slit center in arc seconds, and object position Ra/Dec (six columns).

Output Slit Region File: full name of the SAOImage Ds9 region file Mascgen will create from the best slit configuration. In order for SAOImage Ds9 to recognize this file as a region file, its suffix must be ".reg". This file can be loaded into SAOImage Ds9 on top of a field image of the sky region to display the CSU Plane and the slit configuration. Figure 4 is an example of the region file display.

Output Bar Position List: full name of the text file Mascgen will create to store the 92 horizontal bar positions. The positions are given in arc seconds, with

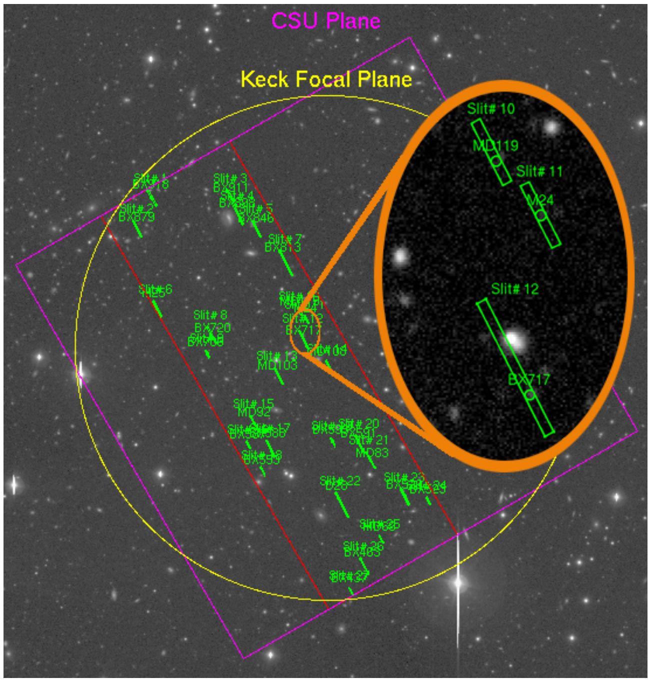

FIG. 4.— CSU Plane with superimposed example slit configuration region file. The magnified inset shows the boxes representing slits and the circles representing objects. The X Range parameter is 2, the X Center is -0.75, and the position angle is 30°.

0" being the center of the CSU. This is a single-column file; the row number serves as the bar number. So, the first row of the file contains the position of bar 1, the second row contains the position of bar 2, and so on. The bars are numbered left to right and top to bottom. In other words, bar 1 is the top left, bar 2 is the top right, bar 3 is the second to the top left, bar 4 is the second to the top right, and so on.

6. OPTIMIZATION ALGORITHM

At its core Mascgen uses a three-pass algorithm (the *optimize* method or routine) to assign slits to target objects. The algorithm employed is

1. For each CSU bar row, scan its accessible zone and assign a slit to the object within the zone with the highest priority. It is possible the slit will not be assigned.

2. On the second pass, check each zone "between" bars (the overlap region plus the user-defined dither space) for objects. Assign two slits to any object, thus forming a "double slit", if such an assignment would increase total priority.

3. On the final pass, assign any unassigned bar rows to the adjacent slit with the highest priority to lengthen an already-assigned slit and use any unassigned bar rows.

In general, if any two objects lie in the same row and happen to have the same priority, Mascgen gives preference to the object that lies closer to the center of the X Legal Range.

The optimize method is run for each combination of CSU center position Ra/Dec and position angle. Mascgen uses an iteration algorithm (discussed in the following section) to test multiple combinations of adjacent center positions and position angles and find the optimized slit configuration that yields the highest cumulative priority.

The optimize method is good, but it is not perfect. In most cases with typical input object lists this method will return the absolute best slit configuration for the given center position and position angle. However, there are circumstances under which the method returns a less than optimum slit configuration. This known fault stems from step 2, where double slits are formed when the priority of an object in the "between" zone is greater than the sum of the highest-priority objects which lie in the rows above and below the "between" zone. Just as forming the double slit requires Mascgen to sacrifice the two adjacent single slits, doing so also necessitates the sacrifice of the potential double slits above and below the new double slit. Mascgen does not evaluate this consequence and may assign a double slit incorrectly. Although the chances of this situation are small, they are not non-trivial. To further reduce the likelihood of incorrect slit assignment, Mascgen creates double slits by running step 2 through the list of objects in "between" zones ordered in descending priority.

It is technically possible to re-write the optimize method and eliminate this error. However, it would also require considerably more processing time. The error ripples out from each possible double slit until it hits the edge of the CSU. With a moderate-density input object list, it is likely that most of the 46 bar rows and 45 "between" zones are occupied by at least one object. In this case Mascgen would need to evaluate how the creation of a double slit anywhere in the CSU affects possible slits everywhere else. Each time Mascgen is run with reasonable numbers of iteration steps the optimize method is called thousands of times within the iteration algorithm. For example, if a user input 10 for Number of X Steps, Number of Y Steps, and Number of Position Angle Steps, then Mascgen would call the optimize method 9,261 times. The small chances of an incorrectly assigned double slit are not enough to warrant such an increase in overall program execution time. Hence, the optimize method returns the *near-optimum* slit configuration.

7. ITERATION ALGORITHM

The optimize method quickly finds a slit configuration for a given center position and position angle. However, altering the center position and/or position angle slightly and re-running the optimize method can produce a slit configuration with even higher cumulative priority. To help the user take advantage of this, Mascgen calls the optimize method within an iteration algorithm which automatically shifts the center position and position angle in accordance with the Number of Steps and Step Size input parameters.

Mascgen iterates over three dimensions - CSU x, CSU y, and position angle. It runs optimize on every combination and stores the slit configuration that results in highest cumulative priority. The iteration algorithm is a robust, "brute force" solution for converging on a better slit configuration within a defined region. It is most useful when applied to a small region and with small iterative step sizes. If one attempted to iterate through a large field (on the order of 10' on a side or larger) with the same small step sizes, Mascgen would need to run optimize millions of times. To make this manageable, one could increase the step size. But, this would likely cause Mascgen to skip over the best slit configuration. During development and testing of the program some techniques and guidelines were found to improve Mascgen's iteration algorithm performance. These are explained and discussed in the following section.

8. HINTS AND TIPS

• When Mascgen is initiated with the "Run with CoP" button it disregards the Center Position Ra/Dec input parameter and calculates its own center position (the Center of Priority) to use as the starting point for the iteration algorithm. This CoP is similar to the physical concept of the two-dimensional center of mass. The formula used to find the CoP is:

$$\text{CoP Coordinate} = \frac{\displaystyle\sum_{\text{all objects}} \text{coordinate} \cdot \text{priority}}{\displaystyle\sum_{\text{all objects}} \text{priority}}.$$

This calculation is performed on the entire input object list for both the RA and Dec coordinates of the CoP.

The CoP is usually a good start to finding a slit configuration with high cumulative priority, but it is not infallible. It is always a good idea to look at the Mascgen CSU output Slit Region File and a plot of all the objects from the input object list (from RegGen, discussed below) to make sure that the CSU is being placed so as to contain multiple high priority targets.

• The folder containing this document, the Mascgen .class files, and the .java files should also contain the Java utility program RegGen. RegGen is a general SAOImage Ds9 region file generator with a graphical user interface. It will create a region file of objects if given an input object list in the same format as that required by Mascgen. Every object is given a circular region and a text string containing its name and priority. In addition, the regions are color-coded to help visually identify high and low priority objects with respect to their distance from the average object priority, $\bar{\mathrm{p}}$, as measured in units of standard deviation, σ. The coloring scheme is:

$$\begin{aligned} \text{priority} \leq \bar{\mathrm{p}} - \sigma \quad & \rightarrow \text{red} \\ \bar{\mathrm{p}} - \sigma < \text{priority} \leq \bar{\mathrm{p}} \quad & \rightarrow \text{yellow} \\ \bar{\mathrm{p}} < \text{priority} \leq \bar{\mathrm{p}} + \sigma \quad & \rightarrow \text{magenta} \\ \bar{\mathrm{p}} + \sigma < \text{priority} \quad & \rightarrow \text{blue} \end{aligned}$$

• When deciding the number of iterative steps and the step size it is usually most efficient to have fewer large x steps and multiple small y steps. The reason for this is that shifting the CSU along the x dimension will only affect the few slits that lie near the end of the X Legal Range. However, shifting the CSU along the y dimension can affect multiple slits because it changes the area of sky covered by each bar row and "between" zone. For example, it is best to have high priority objects fall in rows and not "between" zones because doing so frees up an extra slit (transforming a double slit into two singles which have a combined higher priority). Thus, it's a good idea to make X Step Size on the order of arc seconds and Y Step Size on the order of tenths of arc seconds.

The position angle can also have a large effect on the cumulative priority. Rotating the CSU with respect to the sky even a few degrees can push objects into different rows or "between" zones. It is recommended that the Position Angle Step Size be kept small (∼5° or less) when finding the final slit configuration. Additionally, the position angle need not be iterated through an entire 360°. Depending on the situation, it is quite common for iterations from 0° to 90° or 0° to 180° to converge on the same highest total priority slit configuration as an iteration from 0° to 360°. Iterating through one quarter of the circle will require only one quarter the processing time.

• There are many different ways to employ Mascgen to find the high-priority slit configuration within a field of interest. One could use a tight iteration around the CoP consisiting of thousands of optimize runs. Or, one could patiently step through the entire field of interest to make sure not to miss anything. However, through testing the program we have found one method that consistently produces good slit configurations with a minimum of processing time.

Start by plotting the output of RegGen and looking at the distribution of objects. Try to find where the CSU should be placed by eye and write down the center position. Then, execute a quick run of Mascgen using the CoP option and compare its final center position with the one previously found by eye. Run Mascgen again with the same input parameters, but use the center position found by eye and compare its total priority with that of the first run. Stick with the center position that yielded the highest total priority and now initiate a long Mascgen run (at least 10,000 iterations) to converge on the best slit configuration. Make sure to plot both this slit configuration and the RegGen output to see if anything important was missed or if Mascgen should be rerun with different input parameters.

• The most important thing one can do to get the most out of Mascgen is to learn how it works. It's not a particularly complex program and it might be beneficial to look at the source code and see what's really going on. This paper is a rough introduction to Mascgen; a great deal of minutia has been left out to make the paper digestible. If you have any rudimentary programming background, go ahead and open up the source files and poke around. They are commented and can explain everything that the program does. Also, please feel free to contact the author with questions, suggestions, or bug/glitch reports.

9. ACKNOWLEDGEMENTS

This work was funded in part through the Mr. and Mrs. John H. Glanville & Mr. and Mrs. George H. Jewell Summer Undergraduate Research Fellowship. The author would like to thank his advisor, Chuck Steidel, for support and guidance throughout the development period. He additionally acknowledges the assistance provided by Jason Weiss in developing and optimizing the Mascgen program.

REFERENCES

Slitassign by Kurt Adelberger, 1997.

Autoslit by Judy Cohen, Patrick Shopbell, and Douglas Clowe, 1997.