

An Advanced, Three-Dimensional Plotting Library for Astronomy

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Abstract: We present a new, three-dimensional (3D) plotting library with advanced features, and support for standard and enhanced display devices. The library — `s2PLOT` — is written in C and can be used by C, C++, and FORTRAN programs on GNU/Linux and Apple/OSX systems. `s2PLOT` draws objects in a 3D (x, y, z) Cartesian space and the user interactively controls how this space is rendered at run time. With a `PGPLOT`-inspired interface, `s2PLOT` provides astronomers with elegant techniques for displaying and exploring 3D data sets directly from their program code, and the potential to use stereoscopic and dome display devices. The `s2PLOT` architecture supports dynamic geometry and can be used to plot time-evolving data sets, such as might be produced by simulation codes. In this paper, we introduce `s2PLOT` to the astronomical community, describe its potential applications, and present some example uses of the library.

Keywords: methods: data analysis — techniques: miscellaneous — surveys — catalogs

1 Introduction

1.1 The Status Quo

Visualization is a key tool in astronomy for discovery and analysis that is used throughout the discipline. In observational astronomy, data display applications are used from the observation planning stage through data collection and reduction phases, to production of figures for journal articles. In theoretical astrophysics, data display is an essential process in comprehending nearly every simulation data set, and in summarising results for publication.

Most existing astronomy display tools operate in the two-dimensional (2D) paradigm. That is, multi-dimensional data is explicitly reduced to a data set having at most two ‘look-up’ coordinates (or indices) into the data prior to being presented to a display device. Examples of 2D display packages widely adopted by the astronomy community include the `DS9` image display tool¹, the `PGPLOT` programming library², and third-party commercial packages such as `IDL`³ and `MONGO/SUPERMONGO`⁴.

The dominance of the 2D display paradigm is a simple consequence of both the primary publishing medium (paper) and display device (computer monitor) being inherently flat and two-dimensional. Additionally, the computational demands of 2D graphics display are typically much smaller than those of three-dimensional (3D) display. In this paper, by ‘3D display’ we mean that a set of geometrical objects (or ‘geometry’) is described

— by the programmer and/or software user — to the underlying graphics system using a full three-dimensional coordinate system. The device itself may then produce a 2D view of the content (e.g. on a standard desktop monitor); it might render the content to an immersive display (e.g. a dome) that gives implicit depth perception cues; or it might produce a genuine *stereoscopic* visualization that presents slightly different views of the geometry to the viewer’s left and right eyes.

Historically, the few 3D visualization tools that were developed did not achieve widespread use because processing speed limited their interactivity. For example, the `KARMA XRAY`⁵ package, developed more than ten years ago for volume rendering tasks, was not always able to reach usable rendering speeds on the desktop workstations available at that time, as it relied on the processing power of early Sun SPARC processors.

This is no longer the case: the astronomers’ publishing medium now enables web-based colour graphics, animation and even interactive content; cheap 3D display devices are becoming available; and the computational demands of 3D graphics are now easily handled by off-the-shelf, hardware-accelerated graphics cards that ship with nearly every desktop and laptop computer sold today. The explosion of availability of very fast graphics cards, fed by the massive computer game and entertainment market, now means that the most powerful processor in a desktop computer is often the graphics processor, not the CPU. With specialized circuitry for placing graphics primitives into a 3D virtual space and rendering a view of that space directly to the

¹ `DS9` – hea-www.harvard.edu/RD/ds9

² `PGPLOT` – www.astro.caltech.edu/~tjp/pgplot

³ `IDL` – www.rsinc.com/idl

⁴ `SUPERMONGO` – www.astro.princeton.edu/~rhl/sm

⁵ `KARMA XRAY` – www.atnf.csiro.au/computing/software/karma

screen buffer, displaying 3D environments on desktop computers is now practical and effective.

Evolution of the academic publishing medium, together with the wider availability of advanced computer graphics hardware, has led us and our collaborators to pursue the 3D display, analysis and publication paradigm. Specifically:

- Beeson et al. (2003) report on the development and implementation of a distributed volume rendering technique with stereoscopic support;
- Beeson et al. (2004) present a web-based tool for presenting multi-dimensional catalogues in 3D form via VRML technology; and
- Fluke et al. (2006) report on new, economical versions of traditional display techniques such as dome and tiled wall displays.

The Virtual Observatory paradigm (Quinn et al. 2004) is also suggesting new ideas, and `VOPlot3D`⁶ is an interesting development. It is a Java applet that presents a 2D projection of a 3D point-based data set (extracted from a user-supplied multi-column catalogue) and enables rotation, panning and zooming of the view. In Rixon et al. (2004), the re-casting of the distributed volume renderer (`dvr`; Beeson et al. 2003) as a Grid-enabled application for remote server-based visualization was presented and discussed. The Remote Visualization Service (RVS)⁷ is a nice example of the adaptation of sophisticated, legacy astronomy visualization software to the server-side visualization model, and while it does not (presently) offer 3D viewing capabilities, the plans for RVS always included the eventual incorporation of volume rendering (via `dvr`) as an advanced feature.

A high-profile example of a multi-dimensional data visualization system is provided by the UK National Cosmology Supercomputer⁸. This system builds on the server-side visualization model to provide access to multiple visualization services from low-end, graphically ‘primitive’ desktop computers. The user (client) runs one of `IRIS EXPLORER`, `PARTVIEW`, or `VIS5D+` on their workstation, and controls the rendering parameters locally, but the visualization itself is generated on the server, which provides substantial processor, memory, disk and graphics resources. The rendered image is compressed and transferred back to the client machine for display. This is a nice but central-resource-hungry system that provides non-stereoscopic 3D display services.

The visualization field in astronomy has become very active recently. However, on the whole, the uptake of the new programs for displaying and analysing data is exceedingly low, and it is fair to say that many in the

community would view them as ‘toys’; they demonstrate a neat or useful idea, and might be useful occasionally. They generally do not yet consider any of these systems as standard, in the league of `PGPLOT`, `MIRIAD`, `IDL` and so on. Because of this, the new tools are not installed and potential users are not exposed to them. Consequently there is no de facto or standard library for 3D visualization and display. As an aside, many of the above tools are actually very simple to use once installed, and are generally very well documented.

1.2 Community Behaviour

In view of the above, it was felt that consulting the community to assess their *current* practices in astronomy data visualization and analysis might assist in the future development of visualization tools that astronomers will find useful and *want* to adopt. To this end, Fluke et al. (2006) report on their Advanced Image Displays for Astronomy (AIDA) survey of Australian astronomers. While based on a moderately small sample of forty-one astronomers, it is the best information we have on the behaviour and habits of the community in this domain.

Visualization and Analysis Environment. Excluding wavelength-specific software from Fluke et al. (2006) Appendix A Table 4, we find that the most common analysis tools are: Custom `PGPLOT` tools (regularly used by 44% of respondents), `KARMA` (39%), `MONGO/SUPERMONGO` (34%), `IDL` (29%), and other locally developed software (27%). With the exception of `KARMA`, all of these are actually programming or scripting environments or libraries that provide functionality to use from program code. In fact, `KARMA` *does* provide a programming library and interface, but we know of no current Australian astronomers using the `KARMA` library as opposed to its pre-packaged tools such as `KVIS`, `XRAY`, etc. This is in stark contrast to the recent developments described earlier, which were all pre-packaged, ‘out-of-the-box’ applications for displaying or analysing data, and none of which provided anything like a well-documented *programming* interface or scripting language, yet the results of the AIDA survey suggest a preference amongst astronomers for this approach!

Visualization and Analysis Plot Type. From table 5 of Fluke et al. (2006), we learn that the dominant graph/plot types used by astronomers are 2D graphs, histograms and plots (used by 95% of respondents). Beyond that, 85% regularly display/produce 2D images, and 27% 3D images. We expect that the respondents using ‘3D images’ as a visualization method are including both 2D slices from 3D datasets, and also volume rendering. There are no major surprises here.

Display Device. Participants in the AIDA survey were asked about their experience of display devices, ranging from the ubiquitous CRT/LCD desktop monitor and single-screen stereoscopic projection, to the

⁶ `VOPlot3D` — vo.iucaa.ernet.in/~vo/VOPlot3D_UserGuide_1_0.htm

⁷ RVS — designed and developed by the CSIRO Australia Telescope National Facility, see www.atnf.csiro.au/vo/rvs/

⁸ COSMOS — www.damtp.cam.ac.uk/cosmos/Public/index.html

sophisticated and expensive Virtual Room system. While very few had used anything beyond the standard issue desktop monitor, about 50% of respondents had seen a single-screen stereoscopic projection system in action but had not used such a device personally. Approximately 70% had seen a digital dome projection system, as used in planetaria, but again, had not used the device for their own work. Participants were then asked what factors prevented them from using advanced image displays in their research. Lack of knowledge of available displays was the most common response (approx. 70% of respondents), followed by lack of appropriate software, lack of local facilities and cost (each nominated by around 40% of respondents). Comments made by participants highlighted ‘the time required to develop appropriate tools to take advantage of these displays’ and ‘[the] lack of knowledge of available software’ as key factors preventing higher uptake of advanced display use in astronomy in Australia.

1.3 Responding to the Community

Based on the outcomes of the AIDA survey, we set about deducing which capabilities were most needed in a package that would positively encourage astronomers to begin using advanced, 3D plotting techniques. With recent experience of developing several advanced visualization tools, and the skills and knowledge in advanced displays built up at our institute, we have set about sharing this capability with the astronomy community in a form that we hope will experience significant uptake. That is, we have created an advanced visualization library with the following key features and benefits:

- (1) *provides three-dimensional plotting functions* — dramatically increases capacity and options for display of multi-dimensional data.
- (2) *provides a mechanism for navigating the 3D world* — drastically improves comprehension of 3D geometry, and perception of depth on 2D devices.
- (3) *is a programming library* — can be called from existing and new C, FORTRAN, and C++ codes.
- (4) *has a PGPLOT-like interface* — many of the functions will look familiar to PGPLOT users.
- (5) *works on GNU/Linux and Apple/OSX* — available for the most common astronomer workstations/laptops.
- (6) *works on standard monitors* — enables users to create and explore 3D geometry at their desktop, without requiring expensive hardware.
- (7) *works on advanced displays* — if a stereoscopic or dome display is available, it can be used with no change to the code.
- (8) *comes with documented sample programs* — allowing new users to learn by example.
- (9) *is a binary distribution* — no compilation is necessary to install the library or run the sample programs.

- (10) *can save hardcopy output* — for production of figures and movies for journals and websites. The TGA format is used.
- (11) *can save geometry files* — allowing views to be saved to disk and displayed later without re-running code.

VTK⁹ offers a number of the above features, but it is an extremely heavyweight solution, with an extended learning curve. Additionally, VTK is written in C++, which is not the most popular language of the astronomy community. IDL (versions 5 and above) now has support for 3D graphics, and *in principle* with some clever coding can generate stereoscopic pairs for projection. We have not seen IDL produce stereographics though, and would be interested to hear from astronomers who have done so.

TIPSY¹⁰ is an application specific to *N*-body simulations: it can display particle positions and velocity vectors from an arbitrary viewpoint. The user can follow selected particle(s) as they evolve, and calculate bulk properties of particle groups. This specialized tool is well-used throughout the *N*-body community, but cannot be programmed to do new things. It would be moderately simple to reproduce the capabilities of TIPSY using the S2PLOT library, thus gaining support for dome and stereoscopic displays, and the capability for extensions to the application.

This paper briefly describes the architecture and implementation of S2PLOT — a library that meets the above specifications and is being made available (in binary form only) to the astronomical community. We then give some specific usage examples, consider some future extensions and uses, and close the paper with directions on obtaining the S2PLOT distribution.

2 Design and Architecture

2.1 STEREO

For the last seven years the Centre for Astrophysics and Supercomputing at Swinburne University of Technology has been responsible for providing visualization services to its own researchers and to the wider Swinburne research community. From time to time, it has also delivered visualization services to external users, including the Anglo-Australian Observatory, and to external researchers/collaborations, including Brent Tully and the 6dF team. Consequently, Swinburne has built up a small but substantially capable set of applications for displaying data from many different sources. Almost without exception these visualization solutions support one or more of Swinburne’s advanced display devices (*viz.* passive and active stereoscopic projection displays, MirrorDome, and The Virtual Room), as well as working on normal desktop workstation displays.

⁹ VTK — public.kitware.com/VTK

¹⁰ TIPSY — www-hpcc.astro.washington.edu/tools/tipsy/tipsy.html

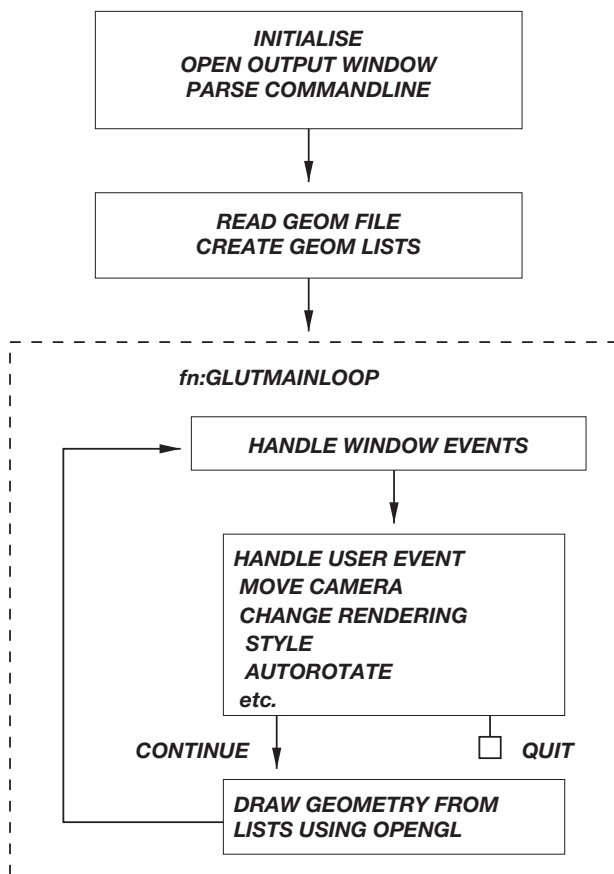


Figure 1 Block diagram of the STEREO2 program flow.

One of these tools — STEREO2 — has a simple but effective architecture that seemed amenable to conversion to a functional programming library. A simple block diagram of the STEREO2 control flow is shown in Figure 1. Very briefly, STEREO2 reads a disk file containing a description of the geometry to be rendered, stores the geometry in a set of lists of different geometry types (e.g., ball, line, quad, textured quad), and then enters its main loop. The main loop draws the geometry using OPENGL¹¹ calls, handles any events coming in via the keyboard or mouse, and loops to draw the geometry again, taking into account any changes (e.g. to the camera location or orientation) made in response to handled events. The main loop is terminated by pressing a special key ('q' or 'ESC') in the display window. STEREO2 supports twenty-one 3D graphics primitives from input referred to as GEOM files.

STEREO2 is fast, fully-featured in terms of graphics primitives, and supports 2D and stereoscopic display devices. It has been built on GNU/Linux, Apple/OSX and Compaq/Tru64 platforms, and has been used regularly at Swinburne for more than three years. It is well-tested and robust, and has been deployed in binary form as a component of scientific visualization theatres installed at sites around Australia and overseas. STEREO2

¹¹ OPENGL — www.opengl.org

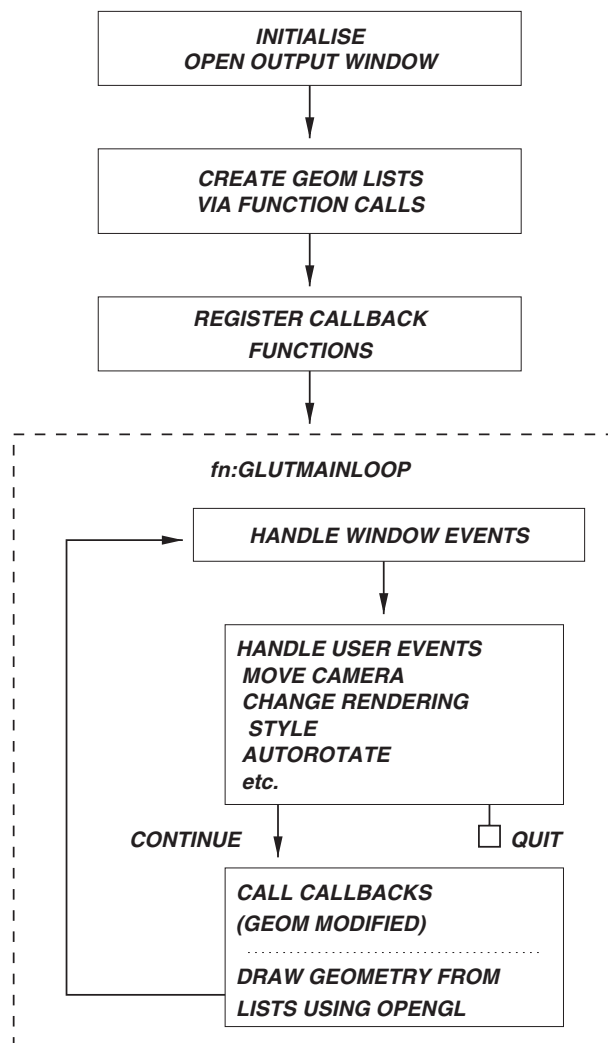


Figure 2 Block diagram of the s2PLOT program flow.

is at 'end of life' and so its code-base is stable and unchanging except for occasional minor bug fixes.

2.2 s2PLOT

The STEREO2 architecture is easily adapted to provide the core of a three-dimensional plotting library. In some sense it is a trivial change: replace the GEOM-format file-reading code with a functional interface whose components explicitly add elements to the lists of geometry types. A simple block diagram of the resulting s2PLOT control flow is shown in Figure 2.

However, there are choices in the style of functional interface. The simplest approach was to write a set of functions that map directly to the 21 primitive geometry types of the GEOM format. We felt that only doing this would miss the opportunity to present an interface that would immediately look familiar and even 'friendly' to many astronomers. Instead we designed a functional interface that replicated many of the functions provided by PGLOT, but using a 3D coordinate system. The viewport (pgsvp) and world-coordinate (pgswin)

functions of `PGPLOT` have obvious 3D generalisations in `S2PLOT`. Consider the `PGPLOT` function

```
pgline(n, xpts, ypts)
```

that draws n connected line segments, joining the points $(xpts[i], ypts[i])$ and $(xpts[i + 1], ypts[i + 1])$ for $i = [1, n - 1]$. It suggests the `S2PLOT` function

```
s2line(n, xpts, ypts, zpts),
```

that draws n connected line segments in a 3D space. Similarly, the `PGPLOT` function

```
pgrect(x1, x2, y1, y2)
```

draws a rectangle extending from $(x1, y1)$ to $(x2, y2)$. It suggests the `S2PLOT` function

```
s2rectxy(x1, x2, y1, y2, z)
```

that draws a rectangle in the xy -plane, extending from $(x1, y1, z)$ to $(x2, y2, z)$. Similarly it suggests `S2PLOT` functions

```
s2rectxz(x1, x2, z1, z2, y), and  
s2rectyz(y1, y2, z1, z2, x)
```

for drawing rectangles in the xz and yz planes. The obvious extension to a more general polygon in 3D is made available through a ‘native’ routine (i.e. one that provides a direct analog of a `GEOM`-format primitive)

```
ns2Vf4(XYZ * P, COLOUR col), and  
ns2Vf4n(XYZ * P, XYZ * N, COLOUR col)
```

that draws a coloured four-vertex facet with normals calculated either automatically (`ns2Vf4`) or specified by the user (`ns2Vf4n`).

With this design, we can go well beyond providing a set of 3D graphics primitives. The `S2PLOT` library provides a world with (linear) coordinates of the user’s choice, and high-level functions that produce parametric line and surface plots, sampled surface plots, axis labels, error bars, colour wedges and so on. The complete set of `S2PLOT` functions based on `PGPLOT`, together with the native functions, provides a comprehensive set of functions for generating 3D realizations of data sets. Not *all* of the `PGPLOT` primitives were suitable for the 3D implementation: some lack useful counterparts in 3D visualization (e.g. `PGBIN`, `PGHIST`), some are device-specific and not well-matched to (or even possible with) the output device for 3D graphics (e.g. `PGSCLP`), and others are concerned with interactive input mechanisms that have deliberately been left out of this first release of `S2PLOT` (e.g. `PGCURS`).

3 Implementation and Use

Output Device. `S2PLOT` uses `OPENGL` calls to display 3D geometry, and compiles on GNU/Linux and Apple/OSX systems. On Linux, its only direct output device is an X-Windows display with the `GLX` extension. This extension is usually provided by the Mesa 3D Graphics Library¹² for software mode (unaccelerated) `OPENGL`, or by drivers specific to the installed graphics card that

provide hardware mode (accelerated) `OPENGL` calls. On a standard OSX installation, the direct output device is the Aqua screen. By virtue of its `STEREO2` heritage, `S2PLOT` provides the following ‘virtual’ output devices:

- `/S2MONO` — non-stereo, perspective display;
- `/S2ACTIV` — active stereo, perspective display;
- `/S2PASSV` — passive stereo, perspective display;
- `/S2FISH` — non-stereo, full fisheye projection;
- `/S2TRUNCB` — non-stereo, truncated-base fisheye projection; and
- `/S2TRUNCT` — non-stereo, truncated-top fisheye projection.

Non-stereo display is always possible and is suitable for desktop monitors and single projector audio-visual systems. Passive stereo mode produces a double-width window containing left-eye and right-eye views of the geometry, suitable for display on X-Windows systems that use extensions (e.g. ‘Xinerama’) to deliver output to a crossed polarisation, two-projector system. Active stereo refers to frame-sequential stereo, which is available on desktop and projection systems with synchronized LCD shutter glasses.

The `/S2FISH` device is available for use in a system providing direct projection through an ideal, 180-degree fisheye lens. The truncated-base fisheye projection is the projection used in `VisionStations`, and the truncated-top projection is that used by planetaria with fisheye lenses. Selectively truncating the fisheye projection enables some optimisation of resolution across the projection surface at the cost of typically one-quarter of the display surface remaining unused. Swinburne’s dome projection device, `MirrorDome`, is supported by `S2PLOT`, but only at licensed sites.

Full-screen display mode is available with all devices by appending the character `F` to the device name. It is to some extent dependent on the window manager in use. With appropriate hardware, the ‘flat screen’ display devices (`/S2MONO*`, `/S2ACTIV*`, and `/S2PASSV*`) can be used to drive multi-projector systems whose individual outputs are ‘tiled’ to generate a large, very-high-resolution display. For example, an off-the-shelf Apple G5 system equipped with an XGA splitter on each of its two video outputs can drive four XGA projectors to deliver a display of 2048×1536 pixels. By adding three dual-output video cards to the G5’s expansion slots, this display can be extended to 4096×3072 pixels! Most of the non-full-screen modes are made available only for testing and development. Almost all production projection systems use full-screen mode to obtain maximum resolution across the projection surface.

Hardcopy output is available, either in ‘one-shot’ mode or continuous recording. The displayed window (including both eye views for stereo mode rendering) is saved to an image file having the same dimensions as the display window. Geometry can be saved to a `GEOM`-format file for later viewing with the included utility `s2view`, and camera location and configuration can also

¹² Mesa 3D — www.mesa3d.org

be saved. Continuously recorded images can later be assembled into movies using third party utilities.

Device and World Coordinates. The primary `s2PLOT` state variables include the location of the current viewport (the part of the 3D world that is being drawn to, defined by the two corners of a 3D box, set by `s2svp`) and the world coordinate values that correspond to the corners of the viewport (set by `s2swin`). All `s2PLOT` functions that produce geometry are called with world coordinates that are internally and linearly transformed to ‘device’ coordinates using the stored state. Since we are concerned with drawing a 3D environment on a 2D screen, there is no real concept of a ‘pixel’ in the 3D space, so device coordinates need not be rounded integers. In fact, the device coordinate system as set by `s2svp`, is largely of no concern to the `s2PLOT` users unless they need to display geometry in a non-cubic space, or they wish to place more than one plot in the 3D space. Once the geometry is complete and `s2PLOT` is asked to display the geometry (see below), the camera location and field-of-view will be set to automatically show the part of the world that is populated with geometry.

The user is free to set a world coordinate system that produces non-cubic environments. In such coordinate systems, the specification of the radius of disks, cones and spheres is not well-defined. `s2PLOT` makes a ‘best effort’ by calculating the quadratic mean of the radius converted to device coordinates on each of the concerned axes. For example, the radius of a disk in the xy -plane in device coordinates is the quadratic mean of the requested (‘world’) radius converted to device coordinates on the x and y axes. Similarly, the radius of a sphere in device coordinates will be the quadratic mean of the requested radius converted to device coordinates on all three axes. Some functions (e.g. `s2circxy`) provide control over this calculation however, and enable the user to draw an ellipse in world coordinates that may or may not look like a circle when viewed (in device coordinates), and to control the aspect ratio of this ellipse. In general, the users will make life much easier for themselves by calling `s2svp` and `s2swin` with equal length axes!

Colour and Light. `OpenGL` provides true 24-bit colour. Thus, any colour requested will be available, and colour-maps (e.g. for surface plots) can have thousands of entries to produce smooth colour gradients. Presently, an arbitrary limit for colourmap size is set at 16384 colours. The lighting for the 3D geometry comprises ambient light of a given colour and intensity, and up to eight point-source lights also of given colour placed in the world.

Labelling. One of the draw-cards of the `PGPLOT` library is its capability to label graphs clearly and sanely. We have included a number of functions in `s2PLOT` that are inspired by `PGPLOT` counterparts, including `s2box` to draw and label the viewport with world coordinates, `s2iden` to write the username and creation date of the plot on the ‘page’, `s2lab` to draw a title at the top of the

‘page’, and `s2env` that provides a convenient wrapper for `s2swin` and `s2box`.

Callback Functions. There is one major difference between the `s2PLOT` and `PGPLOT` programming models. `PGPLOT` allows the user to draw some geometry and show it to the user, and then continue to add geometry to the plot. Conversely `s2PLOT`, via the `STEREO2` code-base, uses the main event loop function (`glutMainLoop`) of the `GLUT` library¹³. This function is responsible for processing and dispatching events to registered handler functions, including refresh and redraw events, and mouse and keyboard events that may modify the camera or geometry settings. The `glutMainLoop` function *never returns*, and as a consequence can be called only once per program invocation. Furthermore, the 3D geometry stored in `s2PLOT`’s internal lists are not displayed until this loop is entered. Hence the programming model, as it stands, requires the users of the `s2PLOT` library to place *all* of their geometry creation function calls *prior* to their call to the `s2PLOT` function `s2show`, which implicitly calls `glutMainLoop`. `PGPLOT` programmers would be quite used to a less constrained model where graphics can be flushed to the device at any time, and as many times as desired. The `PGPLOT` concept of erasing the device or moving to a new page is not present in `s2PLOT`.

To remove this limitation of `s2PLOT`, we have implemented an elegant and powerful mechanism to hand some control back to the programmer. The `s2PLOT` *callback system* allows the users to register their own function to be called once per refresh cycle. If there is no user intervention or excessive CPU load, this refresh occurs up to 25 times per second. The callback function is called by the `s2PLOT` library prior to redrawing the geometry, and two arguments are given to the function: the current time (in seconds) and the number of times a special key (currently the space bar) has been pressed. The programmer can use any `s2PLOT` drawing commands within the callback to produce new geometry for display. The time value can be used to calculate new positions for geometry, and the number of key presses to change some arbitrary state (if desired). We differentiate between *static* geometry that is *created* prior to the one and only call of the `s2show` function but *displayed* every refresh cycle, and *dynamic* geometry that is recreated *and* drawn each and every refresh cycle.

Three key features of the callback function make this a powerful approach to producing scientific and educational 3D content:

- (1) the callback function itself can register another callback function in its place, thus enabling a flow of control from one callback function to another;
- (2) the callback function can disable the callback mechanism, effectively freezing the dynamic geo-

¹³ `OpenGL` Utility Toolkit, originally written by Mark Kilgard of SGI

metry until the user intervenes and re-enables the callback by hitting a special key (currently 'z'); and (3) the callback function can use static local variables in C, or COMMON SAVE'd variables in FORTRAN, to preserve state and data from one call to the next.

Used creatively, these three capabilities can produce innovative programs for display and presentation of data. Some particular ideas will be discussed in Section 4.

Linear Programs. The callback structure can be confusing at first, and most astronomers will not be used to planning or writing callback code. Even though the S2PLOT callback system is straightforward, control of execution is never really available and a linear program structure is still desirable in many cases. Fortunately, two common implementations of the GLUT library provide an extension that make linear programming possible. FREEGLUT, which is standard with many GNU/Linux systems, provides a new function `glutMainLoopEvent()` that 'processes a single iteration of the event loop and allows the application to use a different event loop controller or to contain re-entrant code'.¹⁴ Similarly, Apple's implementation of GLUT for Apple/OSX includes a new function `glutCheckLoop()` that provides precisely the same behaviour. Hence for S2PLOT installations on Apple/OSX and on GNU/Linux with FREEGLUT, the following code fragment becomes possible, and thus the more standard PGLOT programming model is provided:

```
s2open(...); /* open s2plot device */
s2swin(...); /* set world coordinate range */
... /* various calls to create geometry */
s2disp(...); /* display the geometry, let the user interact, and return control when the TAB key is pressed or a timeout occurs */
s2eras(...); /* erase existing geometry */
... /* add further geometry to the world */
s2show(...); /* display again, and this time relinquish control to GLUT */
```

Since the `s2disp` function uses non-standard extensions to GLUT, it should be considered an advanced (expert) feature in S2PLOT and programmers are encouraged to use the callback model where possible.

4 Examples

The possibilities for using the S2PLOT in astronomy and science more generally are essentially limitless. S2PLOT can be used for almost anything from a simple, static plot of the spatial distribution of objects found in a survey such as 2dFGRS, to a dynamic, interactive conference presentation that combines traditional 'POWERPOINT slide' content with pictorial animations running alongside real-time slices of an observational data set. It would even be quite straightforward to integrate S2PLOT visualization

code with data acquisition systems to provide, for example, real-time and multi-dimensional representations of instrument status, data quality, or survey progress. Native support for economical stereoscopic devices and dome projection systems, *needing no additional programming*, opens new horizons in data exploration and visualization for individual scientists and teams of scientists, while 'save now and view later' features mean visualizations can be shared around geographically spread collaborations.

We now describe some examples of S2PLOT use, gratefully received from current users at our institute. Code for some of these examples is available in the S2PLOT distribution. Where suitable, example output is illustrated in this paper in figure form, but we remind readers that static views of three-dimensional geometry are usually a poor substitute for having the ability to view and rotate the data directly on-screen.

4.1 Dome Display of an All-Sky Survey

The Hi Parkes All Sky Survey Catalogue (HICAT; Meyer et al. 2004) is a recent galaxy redshift survey that lends itself well to advanced display and exploration methods. Since it is a survey of the entire southern sky, we have chosen to use it as an example of the dome projection capabilities of the S2PLOT library. Like any wide-field redshift survey, HICAT can be used to visualize large-scale structure at different redshifts. We show in Figures 3 and 4 sample output of a simple S2PLOT program that loads the catalogue, plots the galaxies on the surface of a sphere (the 'sky') and enables the user to select the redshift ranges that are plotted using the numeric keys. Pressing the '1' key toggles the display of galaxies in the velocity range 0–1000 km s⁻¹, the '2' key toggles display of galaxies in the range 1000–2000 km s⁻¹, and so on. The location of two dominant southern clusters — Fornax and Centaurus — are marked by circles in the figures. The sample code for this demonstration is available with the S2PLOT distribution (ASTRO1.C) — see section 6.

4.2 The Structure of Dark Matter Halos

Dark matter halos are the three-dimensional structures in which galaxy clusters and galaxy groups dwell. Their presence and properties directly determine the observed structure in the Universe, and thus the numerical simulation of halo formation can lead to important constraints on cosmological theories. The raw and processed output of *N*-body simulations is naturally spatial in nature, and is well-suited to the S2PLOT 3D visualization environment.

Ashley Rowlands, a summer student at Swinburne 2005/06, has compared the shapes of dark matter halos in Λ CDM and Λ WDM cosmologies. A friends-of-friends algorithm was used to generate catalogues of dark matter halo masses and positions from the zero-redshift simulation output, and S2PLOT was then used to display the resulting physical halo distributions. For both the new student and his 'seasoned' supervisors, being able to explore the

¹⁴ FREEGLUT API reference, freeglut.sourceforge.net

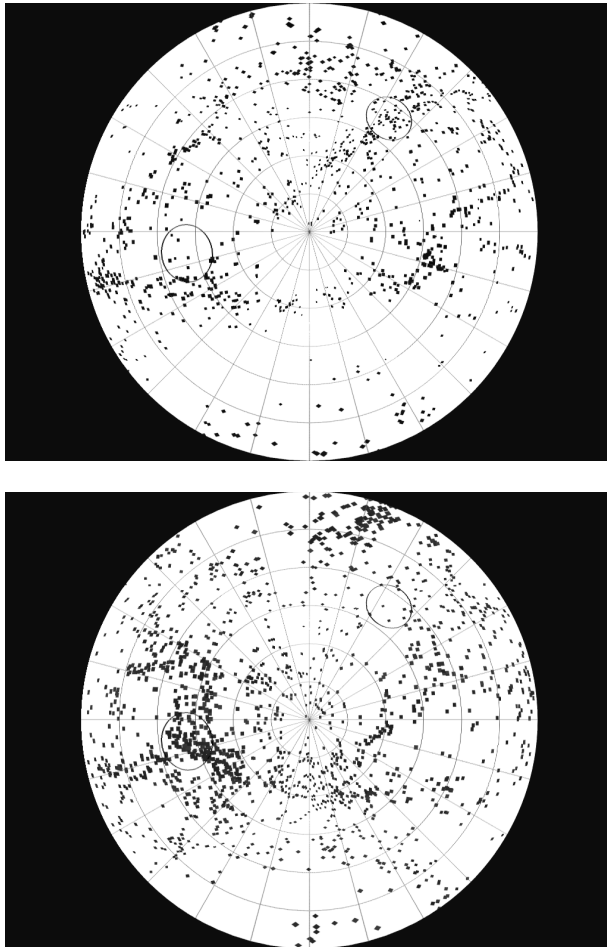


Figure 3 Fisheye projections of southern HICAT galaxies. (Top) Velocity range 0–2000 km s⁻¹. The Fornax cluster is visible in the top-right circle. (Bottom) Velocity range 3000–6000 km s⁻¹. In this velocity range, the Fornax cluster is no longer evident and the Centaurus cluster now dominates the sky (centred in the circle to the left of centre).

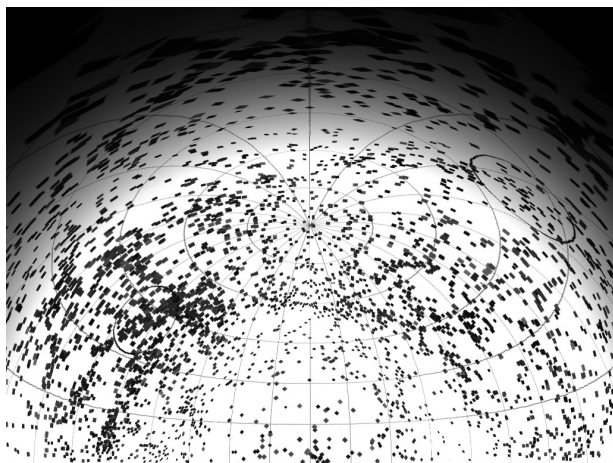


Figure 4 Projection of southern HICAT galaxies in the velocity range 0–10000 km s⁻¹ suitable for display with a Swinburne MirrorDome. Note the extensive (but correct) distortion towards the top and sides of the image where glancing projections off the mirror occur, and the deliberate dimming of the image to maintain uniform brightness over the dome.

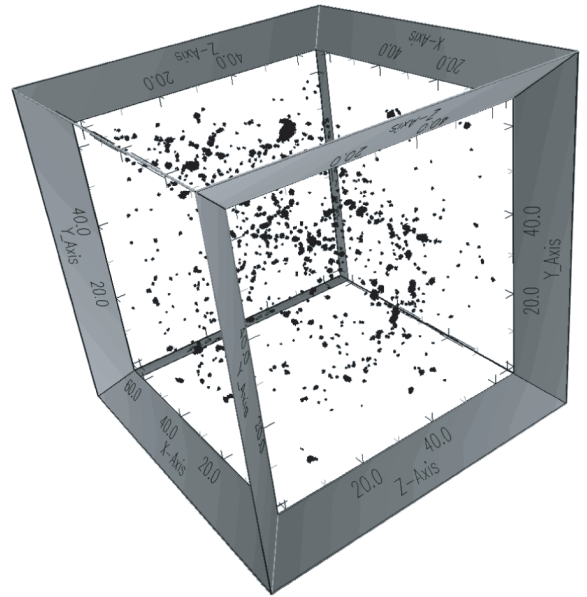


Figure 5 Overall view of halo distribution in a Λ WDM simulation in a $64 h^{-1}$ Mpc box.

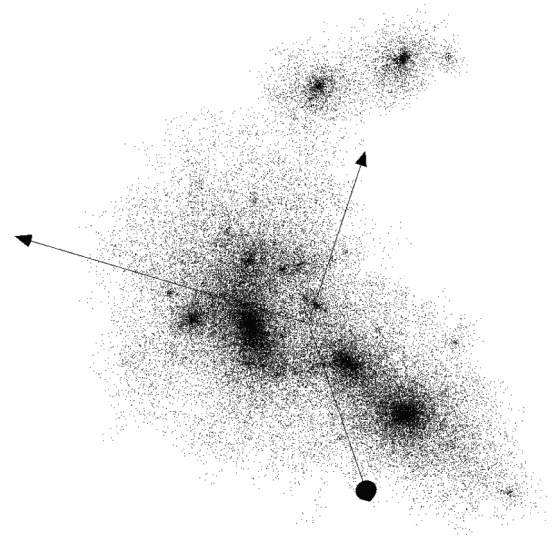


Figure 6 Zoomed view of a section of the halo distribution of the previous figure. Real-time rotation of the visualization, and/or stereoscopic display of same, conveys substantially more information than this figure can.

structures so quickly and easily, directly from their program code, was reportedly very useful. Sample `s2PLOT` visualizations of the data are shown in Figures 5 and 6.

4.3 LVHIS – Local Volume H_I Survey Analysis

The Local Volume H_I Survey (LVHIS) aims to study gas-rich galaxies in the local volume ($D \sim 10$ Mpc or radial velocity $V_{LG} < 550$ km s⁻¹), through 20-cm continuum and H_I line observations. One source of LVHIS targets is the Catalog of Neighbouring Galaxies (CNG) by Karachentsev et al. (2004), an all-sky catalog of 451 galaxies with

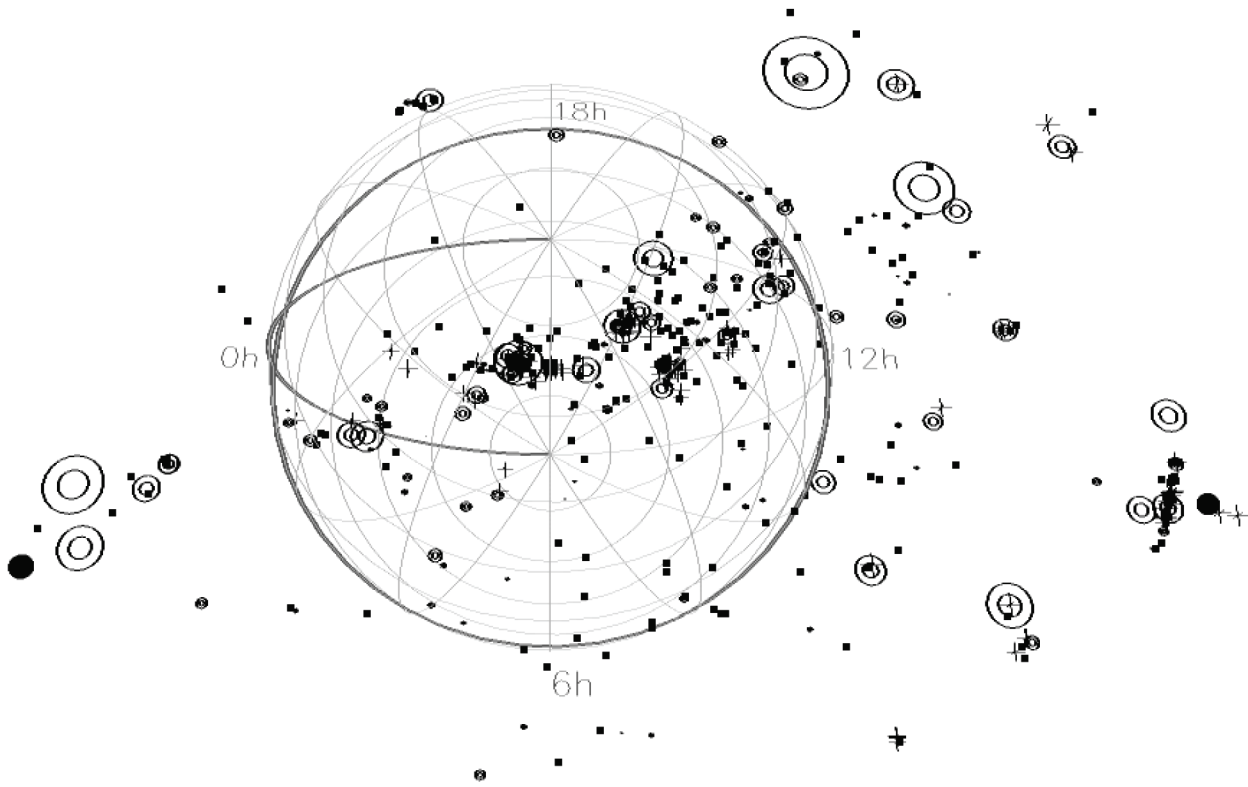


Figure 7 Three-dimensional view of the LVHIS targets. See text for a description of the symbols.

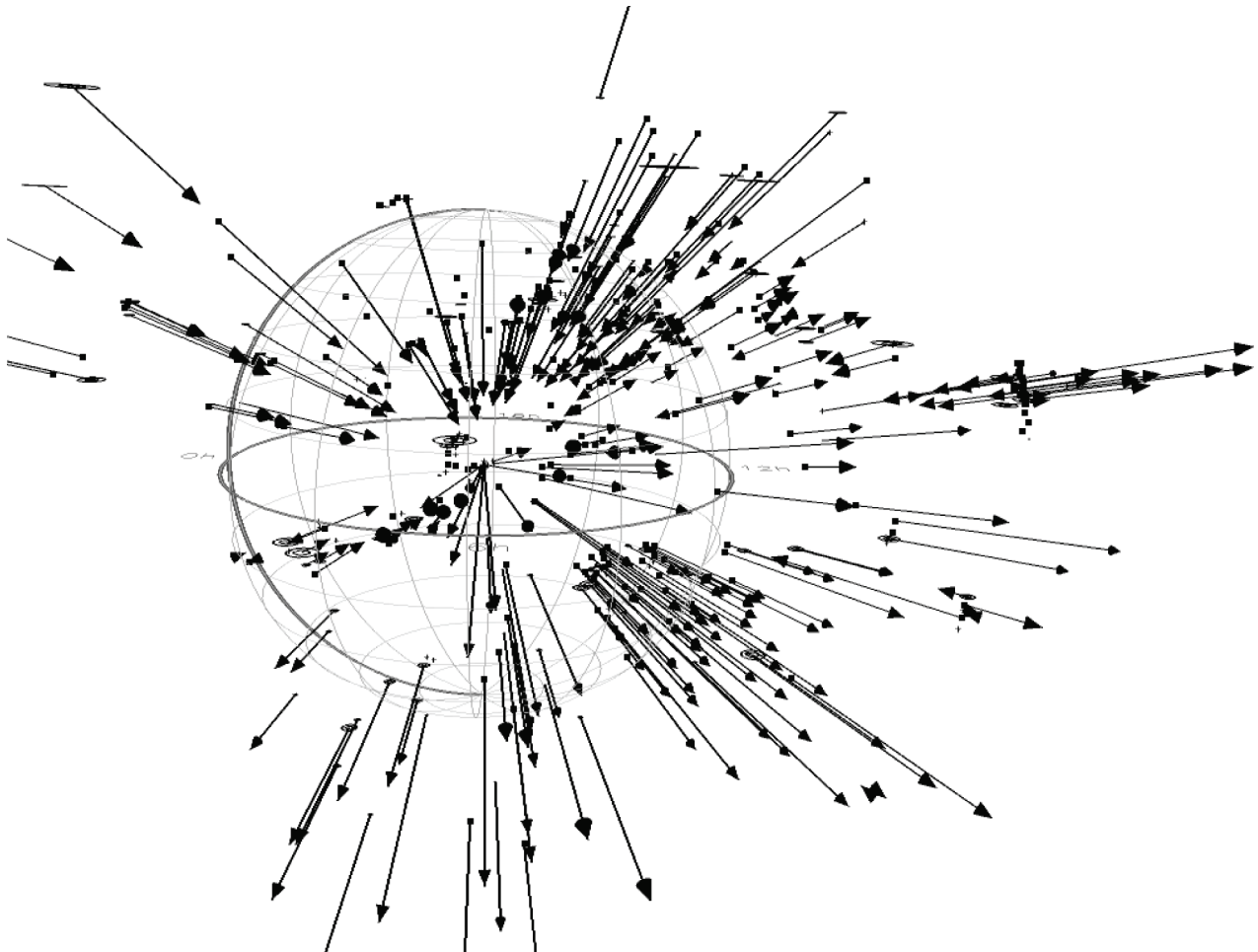


Figure 8 Three-dimensional comparison of galaxy distance measures for the LVHIS sample. See text for further information.

$D < 11.4$ Mpc. Examples of s2PLOT visualizations of the CNG dataset are shown in Figures 7 and 8.

Figure 7 shows the three-dimensional spatial locations of galaxies using RA, Dec and distance converted into (x,y,z) triples. Distances are determined from one of: Cepheid variables, luminosity of the tip of the red giant branch, surface brightness fluctuations, luminosity of the brightest stars, the Tully–Fisher relation, membership in known groups or a direct application of the Hubble relation. Elliptical galaxies are shown as shaded spheres, S0 galaxies as 3D crosses and spirals with measured angular diameter as disks (a second disk is present for those systems where an H α flux has been measured, although the diameters of these H α disks are not well known at present). Spirals without measured diameters and all other object types are indicated by points. The reference grid of right ascension and declination coordinates has radius 5 Mpc, with RA = 0^h and Dec = 0° indicated by a thicker line width. The view is down the axis from positive to negative declinations. A deficit of galaxies between RA 15^h and 24^h is readily apparent, and the Super-galactic plane is visible (particularly when viewed interactively or with a stereoscopic display). Limitations in the distance model are also apparent: note the galaxy group in the lower right-hand quadrant where all group members have been placed at the same distance.

Figure 8 shows the differences between the original measurement of distance, and a value based on the measured heliocentric radial velocity (converted to distance using a Hubble constant of 72 km s⁻¹ Mpc⁻¹ without further velocity corrections). The view is taken almost parallel to the equatorial plane. Systematic differences between the velocity distance and the other distance methods are apparent. The galaxy group identified in Figure 7 is now in the upper right quadrant, and it is apparent that each group member has a different radial velocity. There is also evidence of coherent large-scale velocity flows towards the centre at positive declinations and away from the sphere at negative declinations. A future investigation of this dataset could include an examination of the systemic differences between each distance method.

4.4 RAVEing in the ChromaDome

4.4.1 RAVE

RAVE, the RAdial Velocity Experiment, conducted with the 6dF spectrograph on the UK Schmidt telescope in Australia, will provide an all-sky medium resolution map of the Galaxy. As an exercise in determining how straightforward s2PLOT is for studying new datasets, the RAVE first data release (DR1) comprising 25 274 radial velocities from a region ~ 4670 square degrees was obtained in the week following its announcement. After minimal coding, the s2PLOT visualization of DR1 shown in Figure 9 was obtained. In this figure, DR1 stellar

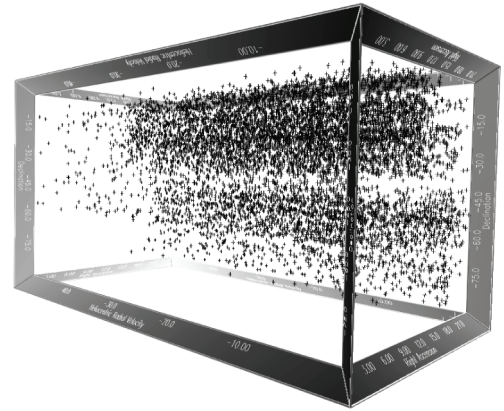


Figure 9 The RAVE Data Release 1 (DR1) with radial velocities (v_r) plotted versus celestial coordinates (right ascension and declination). Only stars with $-50 \text{ km s}^{-1} \leq v_r \leq 0 \text{ km s}^{-1}$ are shown.

positions are plotted in celestial coordinates (right ascension and declination) with heliocentric radial velocity, v_r , providing the third coordinate. Only stars with $-50 \text{ km s}^{-1} \leq v_r \leq 0 \text{ km s}^{-1}$ are shown, and the dataset is best viewed interactively.

4.4.2 ChromaDepth 3-D

Swinburne has recently been developing economical, multi-person advanced display devices. One of these — the MirrorDome — is substantially immersive (offering a $\sim 2\pi$ steradian view) and it is desirable to enhance the effect by providing a stereoscopic display. However, using traditional ‘image-pair’ stereoscopy is troublesome in the dome, because maintaining a single uniform audience horizon (i.e. eye-separation vector) is essentially impossible. Even for a *single* observer, image-pair stereoscopy is awkward because the person can move throughout the dome, and orient their optical axis arbitrarily. The required warp for correct dome display ultimately depends on observer location within the dome together with roll, tilt, and yaw. Every single refresh cycle of the display would entail calculating a new warp map to do things properly. We have not yet optimised the warp map code to the extent that this is possible in realtime.

An alternative to image-pair stereoscopy exists in ‘ChromaDepth 3-D’, a technique patented by Richard Steenblik in 1983 (US Patent No. 4397634). It amplifies the natural chromostereoscopic effect that arises from the variation in refraction of different wavelength light: red light focuses further back than blue light does after entering a refraction-based optical lens system such as the human eye. ChromaDepth 3-D is not stereo-pair based: a single image can be produced that looks sensible without glasses, and stereoscopic with glasses. Red objects appear closer (i.e. are in the foreground), and blue objects appear further away (in the background). Objects having colours in the rainbow lying between red and blue fall at intermediate distances.

ChromaDepth 3-D is a viable stereoscopic display technology for MirrorDome. While relinquishing colour choice in generating content, the programmer can produce a realistic depth effect that is observable from all points within the dome and regardless of orientation of the observers head. Unlike conventional anaglyphs, the display looks sane without glasses on, but when ChromaDepth 3-D glasses are worn, the depth effect is quite remarkable.

We have provided functionality in `s2PLOT` to produce ChromaDepth 3-D output on any device. The function `s2loadmap` can be used to place the supplied ChromaDepth 3-D colourmap into `s2PLOT`'s colour registers. Then, function `s2chromapts` or `s2chromacpts` can be used to plot points in 3D space, coloured according to their distance from the camera. In this way, we have viewed the RAVE DR1 data in the MirrorDome. By programming `s2PLOT` to colour the points — using the correct ChromaDepth colour palette — according to velocity, coherent structure in the dataset was easily seen in the 3D immersive environment. The combination of MirrorDome and `s2PLOT`'s ChromaDepth 3-D capability will give an extraordinary view of the survey once it nears completion.

5 Future Possibilities

The brief examples we have given of `s2PLOT` programs only touch the surface of what is possible. The main motivation for developing `s2PLOT` was to provide a simple and effective entry-point to 3D graphics for professional astronomers and astrophysicists. However, as a high-level programming library, `s2PLOT` is genuinely flexible, and we envisage a number of further domains in which it might be useful.

Public Outreach. `s2PLOT` might be used to construct simple models of planetary systems, with the user controlling visual effects such as which planets are displayed and whether their orbital paths are drawn, or more physical parameters such as planet and stellar masses and rotation periods. The user could easily stop and start the simulation, and move to pre-programmed view points to demonstrate tilted orbits, for example. If a MirrorDome system is available, 'immersion' in the simulated planetary system is simple and effective, and concepts such as retrograde motion can easily be explored. Placing a panoramic sky image 'behind' the simulated system (as a texture on the interior of a large-radius sphere) strengthens the immersive feeling and can make `s2PLOT` educational outreach programs exciting and thrilling for young audiences.

Professional Presentation Tools. With the ability to place textures on planes and control animation states it is entirely feasible to write code that uses the `s2PLOT` library to support a presentation at a conference. Standard Microsoft POWERPOINT content can be saved to files for display within an `s2PLOT` program, alongside genuine realtime simulations of the concepts being

discussed, or, for that matter, dynamic display of realtime data streams.

Real-Time Instrument Monitoring. With its callback mechanism, `s2PLOT` can be operated in a mode where the main program does nothing more than open the `s2PLOT` device and register a callback function. This means that real-time instrument monitoring programs can be written with `s2PLOT`. A simple example might entail a callback function that monitors one or more disk files, and creates geometry on each refresh cycle to reflect changes in the files. A more sophisticated callback function could use sockets to connect to other processes, such as image acquisition software, processing routines, or even environmental monitoring applications.

A concrete example is the potential to reimplement the Livedata Monitor client that presents Parkes Multi-beam data in a waterfall-style display. This client could be programmed to display surface-elevation plots of time-frequency data using `s2PLOT`. Inspecting these plots from different viewing angles might offer new possibilities for recognising patterns in radio-frequency interference (RFI). Stacking thirteen plots, one on top of the other, in 3D space might also aid in recognising RFI that is impacting all feeds of the system. For complex cross-correlation data, `s2PLOT` makes time-based plots of one complex variable possible without showing phase and magnitude separately. A product that is steadily rotating in phase, with increasing amplitude, can be plotted as a widening spiral in 3D space.

6 Closing Remarks

We are making `s2PLOT` available to the astronomical community. It is available as a binary library for GNU/Linux and Apple/OSX systems, and is distributed with various sample programs (source code and pre-compiled binaries) as a learning aid. New users can make quick progress by adapting one of the sample programs to their needs and can produce an executable program using the build scripts that are provided with the distribution. Accelerated OPENGL performance should be available by default on Apple/OSX systems, and on GNU/Linux systems where accelerated NVIDIA drivers have been installed. Even without OPENGL-compliant hardware, GNU/Linux systems typically use the Mesa library to provide software-mode rendering. `s2PLOT` requires an installation of the `xFORMS`¹⁵ library. Many distributions of GNU/Linux include `xFORMS`, and it is just a matter of selecting it for installation. Apple/OSX users can obtain a copy of `xFORMS` via `FINK`¹⁶.

`s2PLOT` can be obtained from the following web page:

astronomy.swin.edu.au/s2plot

which contains information on installation, and detailed descriptions of all `s2PLOT` functions.

¹⁵ world.std.com/~xforms/

¹⁶ fink.sourceforge.net

Acknowledgments

We gratefully acknowledge Tim Pearson, for his `PGPLOT` Graphics Subroutine Library, a much-loved package that deserves its place in any collection of astronomical software. `PGPLOT`'s simple, clear interface was an inspiration for many of the `s2PLOT` functions. We also offer our sincere thanks to Tony Fairall for alerting us to the possibility of producing a chromo-stereoscopic display in a digital dome environment. We thank the following users for providing examples of `s2PLOT` use: Katie Kern, Alina Kiessling, Virginia Kilborn, Bärbel Koribalski, Chris Power and Ashley Rowlands. We are also very grateful to the referee for providing valuable suggestions on improvements to this paper.

`S2PLOT` is freely available for non-commercial and educational use, but it is not public-domain software. The programming libraries and documentation may not

be redistributed or sub-licensed in any form without permission from Swinburne University of Technology. The programming library and sample codes are provided without warranty.

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