Exploratory analysis of PDR-1 of the VIPERS galaxy redshift survey

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Abstract

Galaxy redshift data collected through the VIPERS project are explored. VIPERS stands for VIMOS Public Extragalactic Redshift Survey and is an ESO Large Programme. VIMOS refers to Visible Imager Multi Object Spectrograph, an instrument on *Melipal*, the Very Large Telescope (VLT) Unit 3. In October 2013 the first public data release (PDR-1) of the VIPERS project was released to the general public. The present paper demonstrates how this data release can be explored using the open source software R. Data manipulation, visualization and statistical analysis are discussed. Details are provided in a format in which text, executable R code and results are combined, giving an easy to follow approach. This paper shows how hobby astronomers can use publicly available data and open source software to conduct interesting exploration and analysis of astronomical data collected through professional initiatives.

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1 Introduction

In October 2013, the first Public Data Release (PDR-1) of the VIPERS project was released to the general public. VIPERS stands for VIMOS Public Extragalactic Redshift Survey, and is an ESO Large Programme; VIMOS refers to Visible Imager Multi Object Spectrograph, an instrument on 'Melipal', the Very Large Telescope (VLT) Unit 3. Details on VIPERS can be found in Guzzo et al. (2013). Garilli et al. (2013) discuss the public data release specifically. Both are recommended reading in order to fully understand the project and the data. VIPERS will provide a sample of approx. 100,000 galaxies with redshifts $0.5 < z < 1.5$ and absolute magnitudes $i_{AB} < 22.5$. In this paper PDR-1 is explored in some detail.

2 VIPERS PDR-1

The central point of entry for everything related to VIPERS is the project website, http://vipers.inaf.it. This website provides access to a wealth of information, and to the PDR-1 data sets.

Since this data release is almost complete for the W4 field but not for the W1 field (Garilli et al., 2013), only W4 field data are used in this study. The main focus is on the spectroscopic data (redshifts) and not on the photometric data for now. Hence, the relevant file to download is the spectroscopic W4 data, which is offered in different formats; the ASCII file is most convenient for further processing. The file containing the relevant data is named – after unzipping – VIPERS_W4_SPECTRO_PDR1.txt. Descriptions of the columns can be downloaded in text file format[1].

3 Software and dissemination

All analysis conducted on the PDR-1 data are conducted in R (R Core Team, 2012). In addition, following packages are used for additional functionality: ggplot2 (Wickham, 2009) for plots and graphics, ks (Duong, 2012) for the kernel density based two sample test, and deldir (Turner, 2012) for producing Voronoi or Dirichlet tessellations.

A convenient way to share R code and results is to use RStudio (RStudio Team, 2012), an Integrated Development Environment (IDE) for R. It comes with a facility to integrate markdown documents with R code (Allaire et al., 2012) and to combine text, code and R output into a single HTML file; the

[1]The file available for download is named README_VIPERS_SPECTRO_PDR1.txt.

package to achieve this is called knitr (Xie, 2012). From within the IDE, these HTML files can be uploaded to an online repository, RPubs (www.rpubs.org). RPubs is a free web-publishing platform for R Markdown files that have been converted to HTML, and is provided by the RStudio company.

4 Exploration, visualization and analysis

The actual analyzes of the data are contained in the Appendix. They are conducted in RStudio and published to the RPubs repository as discussed in the previous section. The Appendix contains the same content as the document available online at http://rpubs.com/bbuelens/vipersv10.

The analysis steps are summarized as follows. The data are read into the R environment and filtered using quality indicators provided with PDR-1. A coordinate transformation is conducted to convert the spherical coordinates into Cartesian coordinates. A two dimensional representation is obtained by projecting the data onto a plane through the W4 field. The 2D coordinates allow for convenient visualization. In preparation for subsequent analyzes, a rectangular selection of the projected data is made. Apart from a straightforward scatter plot, some graphics routines are used to produce a *pretty picture* of the data. The structure of the galaxies spatial distribution stands out nicely. This distribution is analyzed further, in particular, comparisons with a uniform distribution are conducted. Using a kernel based density estimation the hypothesis is tested that the VIPERS galaxy distribution and a sample generated from a uniform distribution share the same density function. This hypothesis is rejected with a very small p-value, indicating that it is extremely unlikely that the spatial distribution of the galaxies is uniform — an observation confirming intuition. A different approach to spatial distribution analysis is the construction of a Voronoi tessellation, both for the galaxy distribution and for a uniform random sample. The areas of the cells of galaxy data are smaller than those of the uniform data, indicating that the distance to the nearest galaxy is smaller than one would expect had the distribution been uniform. This is illustrated with distribution plots of the areas of the cells of the tessellation.

These analyzes and results are available in full detail in the Appendix, with R code to reproduce everything including the generation of plots and graphics.

5 Conclusions

The analysis presented in this paper is an example of the possibilities available today to hobby scientists in terms of working with data of professional quality collected through scientific observing campaigns. It has become common practice for professional astronomy projects to include public data releases. Such data contain a wealth of information, and offer excellent opportunities for amateurs to perform analytical tasks such as data exploration, visualization, and statistics. The present paper should inspire hobby scientists to conduct similar or related analytical studies using publicly available astronomical data sets.

Acknowledgments

This paper uses data from the VIMOS Public Extragalactic Redshift Survey (VIPERS). VIPERS has been performed using the ESO Very Large Telescope, under the "Large Programme" 182.A-0886. The participating institutions and funding agencies are listed at http://vipers.inaf.it.

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Appendix: RPubs document

This appendix contains the most substantial part of the present paper. The following pages are a representation of the material available online at the RPubs repository. RPubs is an initiative to make available R code, output and documentation, all combined in a single file. The material included here is accessible online at http://rpubs.com/bbuelens/vipersv10, and is introduced and linked to from http://www.astrostatistics.org/projects/extragalactic-redshifts. In future, the latter URL may contain information on additions, updates or corrections to the current material as presented here – tagged version 1.0 and uploaded to RPubs on January 25th, 2014.

VIPERS data exploration, visualization and analysis

Version 1.0, Bart Buelens, 25 January 2014.

www.astrostatistics.org

Introduction

We explore galaxy redshift data collected through the VIPERS project. VIPERS stands for VIMOS Public Extragalactic Redshift Survey, and is an ESO Large Programme; VIMOS refers to Visible Imager Multi Object Spectrograph, an instrument on 'Melipal', the Very Large Telescope (VLT) Unit 3. In October 2013, the first Public Data Release (PDR-1) of the VIPERS project was released to the general public.

The author of this study has no involvement in the VIPERS project and is not affiliated with any of the VIPERS project partners. The analysis presented in this study is an example of the possibilities available today to hobby scientists in terms of working with data of professional quality collected through scientific observing campaigns.

The central point of entry for everything related to VIPERS is the VIPERS project website. This website provides access to a wealth of information, to the PDR-1 data sets, and to some relevant background papers.

More background information about the study presented here, and similar projects, can be found at www.astrostatistics.org. A working paper explaining the analyses presented here is forthcoming.

Acknowledgement This example uses data from the VIMOS Public Extragalactic Redshift Survey (VIPERS). VIPERS has been performed using the ESO Very Large Telescope, under the “Large Programme” 182.A-0886. The participating institutions and funding agencies are listed at http://vipers.inaf.it.

Getting ready

Initial operations needed to get started include loading some libraries we will need, and the data set. We use the spectroscopic data from the W4 field in this example.

```
library(ggplot2)
library(ks)  # kernel smoothing
library(deldir)  # Dirichlet (Voronoi) tessalation
datapath = "D:\\wherever your files are\\"
fileName = paste(datapath, "VIPERS_W4_SPECTRO_PDR1.txt", sep
= "")
V = read.table(fileName, header = FALSE, dec = ".", row.names
= NULL, comment.char = "#")
names(V) = c("VIPERS", "id_IAU", "num", "alpha", "delta",
"selmag", "errselmag",
    "pointing", "quadrant", "zflg", "zspec", "epoch",
"photoMask", "tsr", "ssr")
str(V)
```

```
'data.frame':   30698 obs. of  15 variables:
 $ VIPERS   : Factor w/ 1 level "VIPERS": 1 1 1 1 1 1 1 1 1 1
...
 $ id_IAU   : int  401019899 401031253 401013207 401026127
401027480 401011775 401023109 401024147 401039752 401021131
...
 $ num      : int  401019899 401031253 401013207 401026127
401027480 401011775 401023109 401024147 401039752 401021131
...
 $ alpha    : num  330 330 330 330 330 ...
 $ delta    : num  0.905 0.952 0.876 0.931 0.936 ...
 $ selmag   : num  22.2 20.8 21.6 21.4 21.5 ...
 $ errselmag: num  0.0391 0.0149 0.0219 0.0281 0.0424 0.0275
0.0263 0.0342 0.0392 0.0369 ...
 $ pointing : Factor w/ 93 levels "W4P001","W4P002",..: 1 1 1
1 1 1 1 1 1 1 ...
 $ quadrant : int  3 3 3 3 3 3 3 3 3 3 ...
 $ zflg     : num  2.5 3.5 0 2.5 0 1.5 2.5 1.5 3.5 2.5 ...
 $ zspec    : num  0.819 0.819 10 0.724 10 ...
 $ epoch    : int  1 1 1 1 1 1 1 1 1 1 ...
 $ photoMask: int  1 1 1 1 1 1 1 1 1 1 ...
 $ tsr      : num  0.452 0.448 0.453 0.452 0.452 ...
 $ ssr      : num  0.75 0.905 -1 0.903 -1 -1 0.864 -1 0.838
0.821 ...
```

We filter the data set to retain only those galaxies with reliable redshift measurements. Refer to the VIPERS project website and references from there for details about the variables occuring in the code below.

```
dim(V)
```

```
[1] 30698    15
```

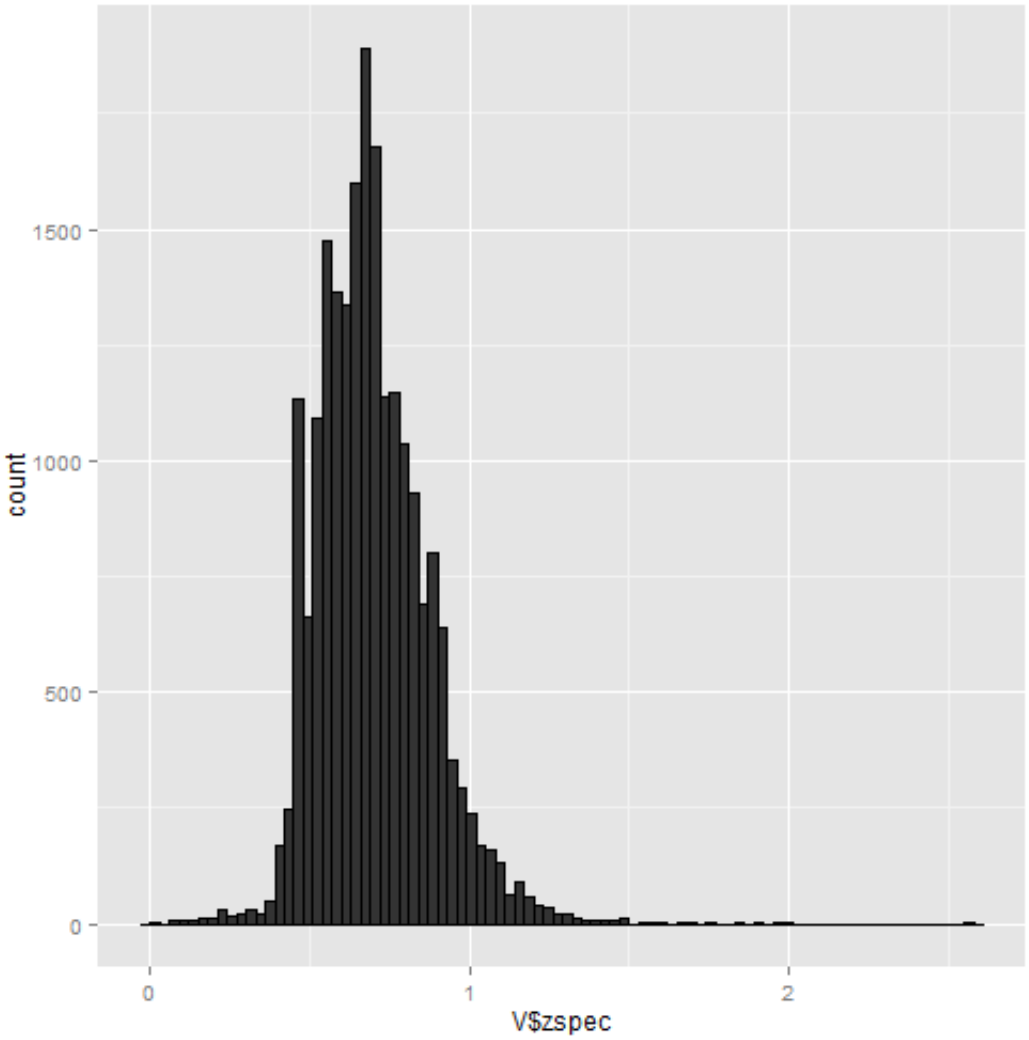
```
V = subset(V, ssr > 0 & tsr > 0)

erf = function(x) {
    2 * pnorm(x * sqrt(2)) - 1
}

csrf = function(x) {
    b = 10.8
    zt = 0.444
    0.5 - 0.5 * erf(b * (zt - x))
}

V$csr = csrf(V$zspec)
V = subset(V, csr > 0)

xtabs(~zflg, V)
```

```
zflg
 2.2  2.4  2.5  3.2  3.4  3.5  4.2  4.4  4.5  9.2  9.4  9.5
1771  317 4067 1665  546 4517 1654 1119 5324  442   30  564
```

```
V = subset(V, zflg < 5 & zflg > 1)  # retain only good
quality data

summary(V$zspec)
```

```
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
 0.0288  0.5770  0.6780  0.6960  0.7960  2.5800
```

```
qplot(V$zspec, binwidth = 0.03, colour = I("black"))
```




```
# almost none at z > 1.2
V = subset(V, zspec >= 0.5 & zspec <= 1.2)
dim(V)
```

```
[1] 18509    16
```

```
# calculate sampling weights:
V$w = (1/V$ssr) * (1/V$tsr) * (1/V$csr)
summary(V$w)
```

```
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max. 
   2.06    2.51    2.69    2.77    2.95    4.76 
```

Data preprocessing

We project the data from right ascension, declination and redshift to a Cartesian system. While not strictly necessary, this will facilitate further analysis.

```
z2d = function(z) {
    # crude linear approximation redshift to distance
    c = 299792  # km/s
    H = 100  # leave h =~ .71 within units ie. H = 100 h km
/s / Mpc
    d = z * c/H
    return(d)  # unit Mpc/h
}

V$r = z2d(V$zspec)
summary(V$r)
```

```
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
   1500    1840    2100    2160    2430    3600
```

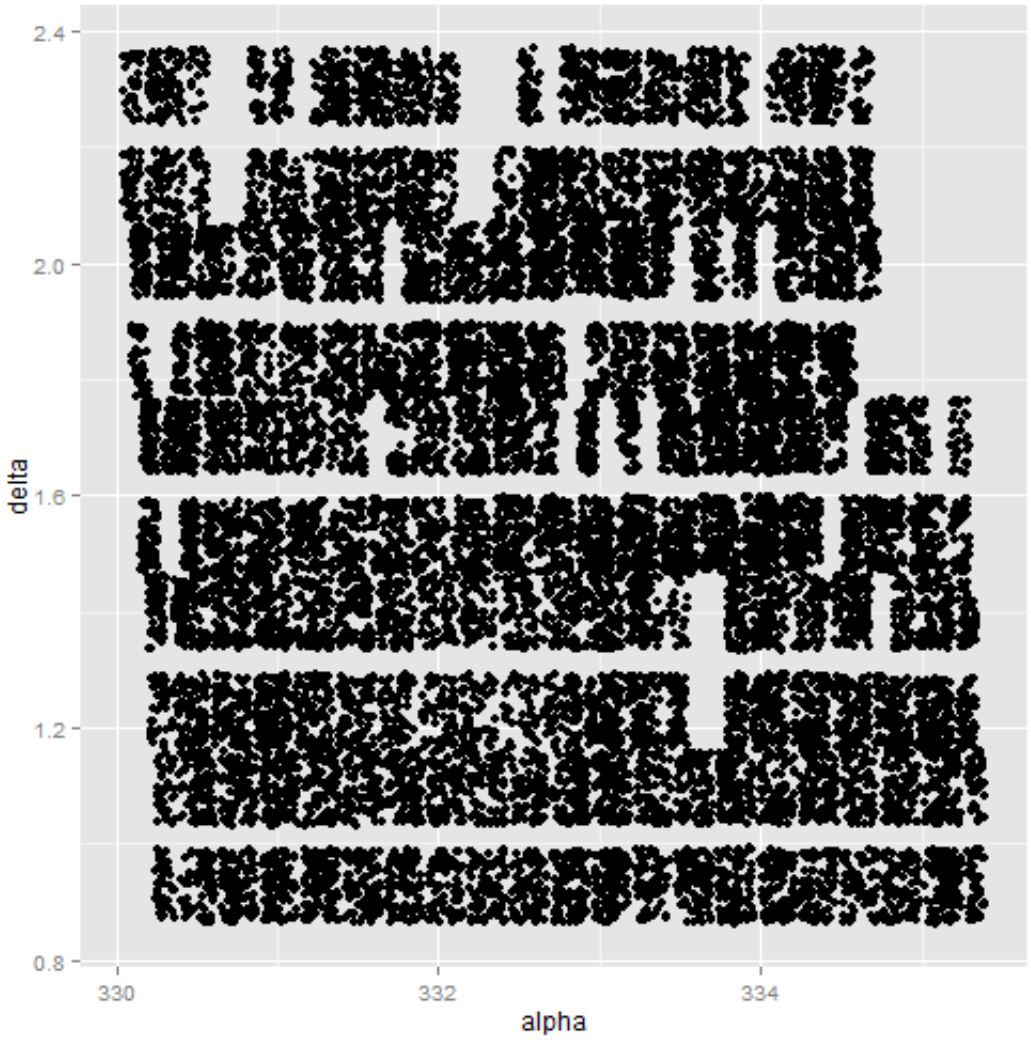
```
summary(V$alpha)  # in degrees, right ascension
```

```
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
    330     331     333     333     334     335
```

```
summary(V$delta)  # in degrees, declination
```

```
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
  0.863   1.200   1.560   1.580   1.950   2.370
```

```

# distribution on celestial sphere:
p = ggplot(V, aes(alpha, delta))
p + geom_point()
```

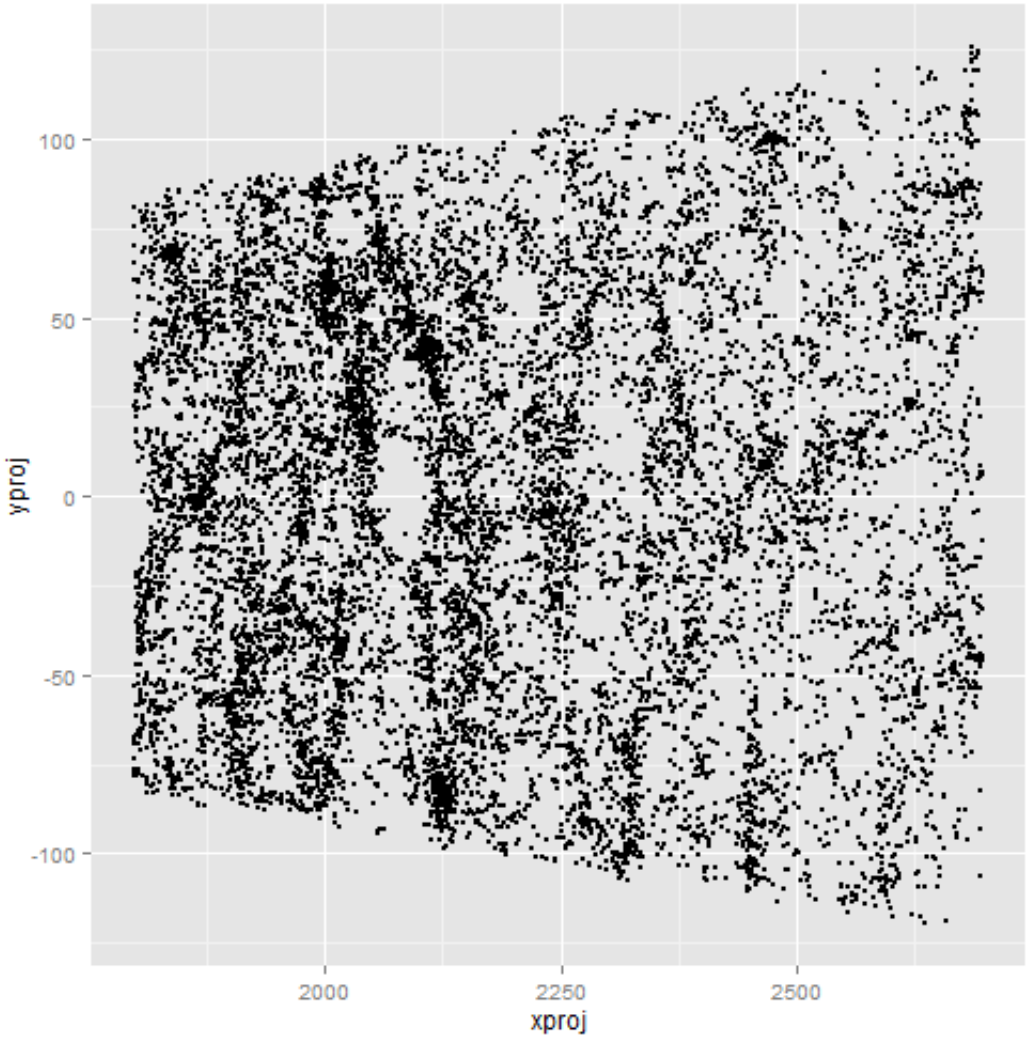



```
# from degrees to radians:
V$alpharad = (pi/180) * V$alpha
V$deltarad = (pi/180) * V$delta

# Cartesian coordinates:
V$x = V$r * cos(V$deltarad) * cos(V$alpharad)
V$y = V$r * cos(V$deltarad) * sin(V$alpharad)
V$z = V$r * sin(V$deltarad)

# Project onto a plane through the observation volume, tilted
to the mean
# declination of all galaxies, with the y-axis rotated to the
mean right
# ascension
deltamean = mean(V$deltarad)
alphamean = mean(V$alpharad)
V$xproj = V$r * cos(V$deltarad - deltamean) * cos(V$alpharad
- alphamean)
V$yproj = V$r * cos(V$deltarad - deltamean) * sin(V$alpharad
- alphamean)
```

Visualization

Analysis of the galaxies will now proceed in the projection plane using the projected coordinates (xproj, yproj). We render the galaxies in this 2D plane in various ways. We select a rectangular window for convenience.

```
ggplot(subset(V, zspec > 0.6 & zspec < 0.9), aes(xproj,
yproj)) + geom_point(size = 0.01)
```



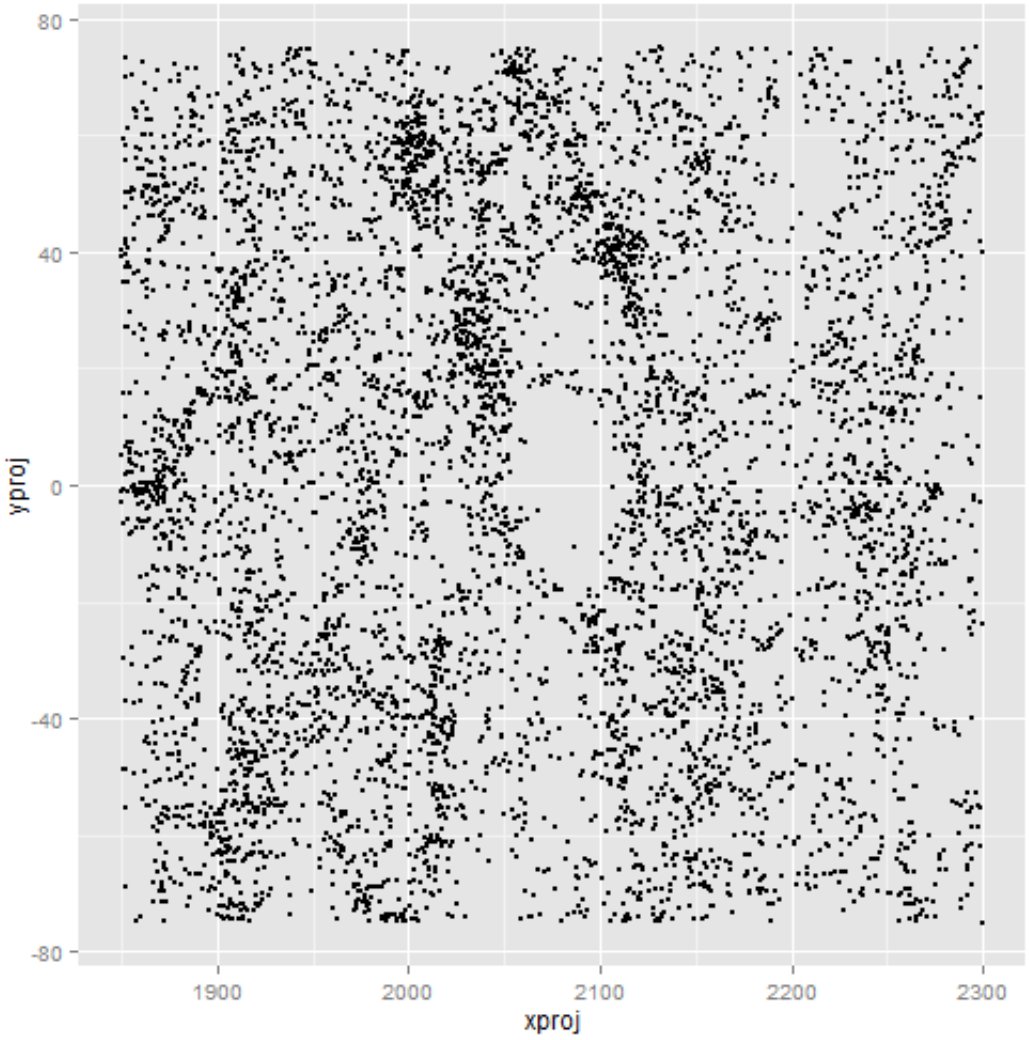

```
# select a rectangular area for convenience:
xmin = 1850
xmax = 2300
ymin = -75
ymax = 75

VS = subset(V, xproj > xmin & xproj < xmax & yproj > ymin &
yproj < ymax)
dim(V)
```

```
[1] 18509    25
```

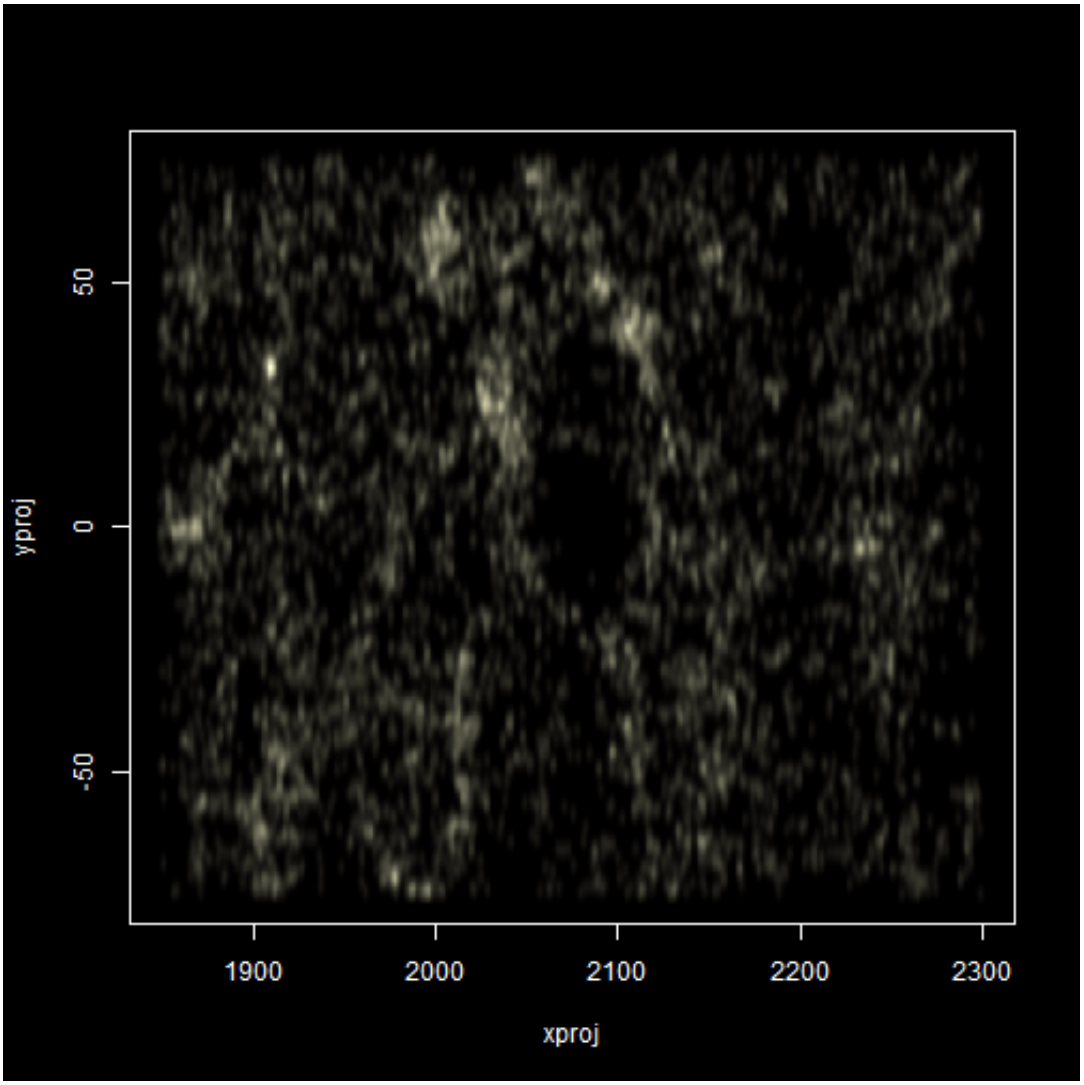
```
dim(VS)  # our selection
```

```
[1] 6375   25
```

```
ggplot(VS, aes(xproj, yproj)) + geom_point(size = 0.01)
```




```
# Visualization of VS in a nicer way
creme = "#FFFDD0"
mycolramp = colorRampPalette(c("black", creme))
mycol = densCols(VS[, c("xproj", "yproj")], colramp =
mycolramp, nbin = 500)

oldpar = par()
par(bg = "black", col = "white", col.axis = "white", col.lab
= "white", fg = "white")
smoothScatter(VS[, c("xproj", "yproj")], nrpoints = 0,
colramp = mycolramp,
    nbin = 500, transformation = function(x) x, bandwidth =
1.3)
```

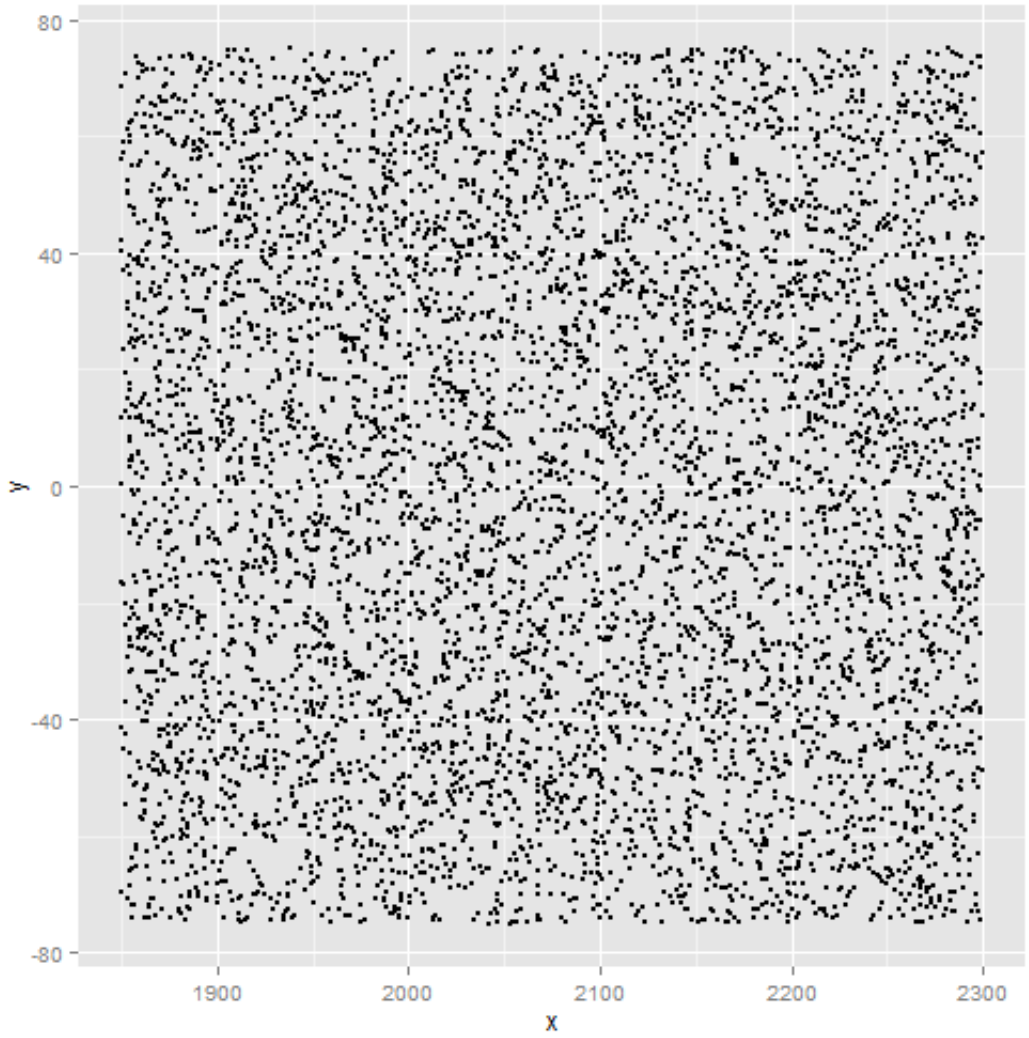



```
par(oldpar)
```

Spatial distribution analysis

Using kernel density estimation, two samples can be compared. The null hypothesis that both are genereated from the same density is tested. To be able to use this test, we generate a random realisation from the 2D uniform distribution. To verify that the test performs well, we test two independently generated unformly distributed samples.

```
# Is the distribution significantly different from uniform?
n = dim(VS)[1]
Udf = data.frame(x = runif(n, min = min(VS$xproj), max =
max(VS$xproj)), y = runif(n,
    min = min(VS$yproj), max = max(VS$yproj)))
ggplot(Udf, aes(x, y)) + geom_point(size = 0.01)
```




```
X = kde.test(x1 = as.matrix(VS[, c("xproj", "yproj")]), x2 =
as.matrix(Udf))
X$pvalue  # highly significant!
```

```
[1] 4.443e-41
```

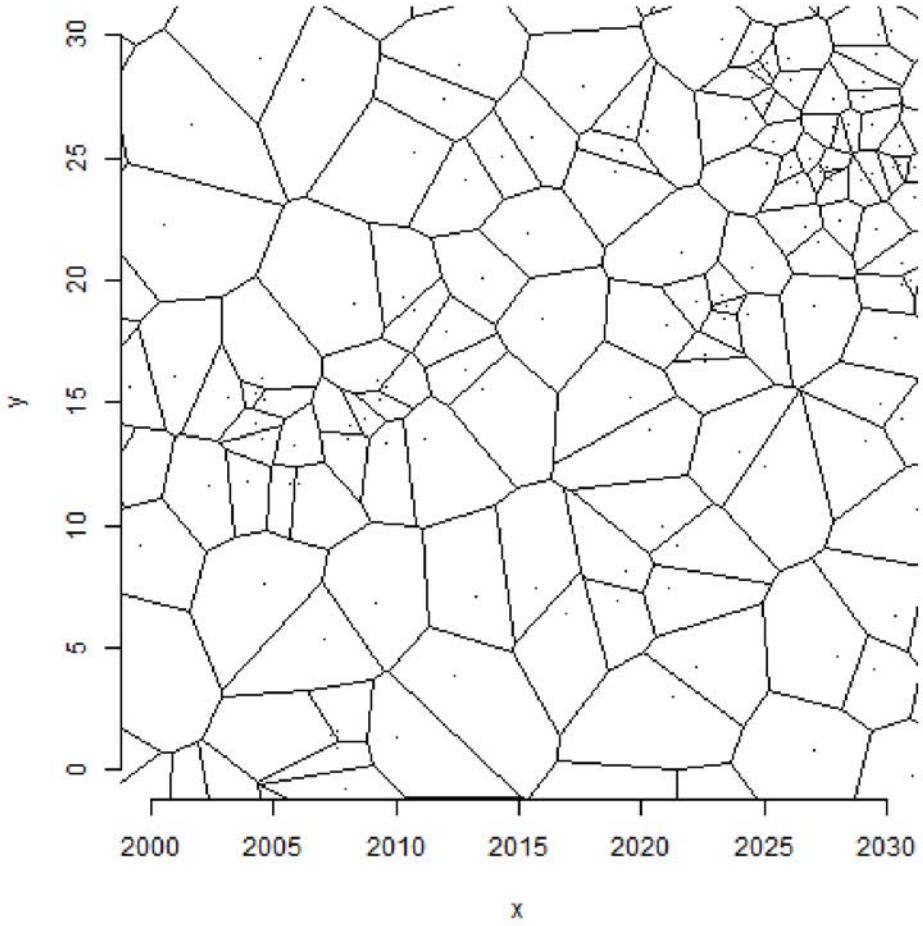
```
# double check this test, and test 2 uniformly distributed
sets
Udfbis = data.frame(x = runif(n, min = min(VS$xproj), max =
max(VS$xproj)),
    y = runif(n, min = min(VS$yproj), max = max(VS$yproj)))
Y = kde.test(x1 = as.matrix(Udf), x2 = as.matrix(Udfbis))
Y$pvalue  # not significant at all, good!
```

```
[1] 0.7226
```

Going by this test and associated p-value, the null that both the uniformly distributed sample and the VIPERS sample follow the same distribution is rejected.

Further evidence that the spatial structure of the galaxies is not uniform is obtained in the following way. We obtain a Voronoi or Dirichlet partitioning, both for the VIPERS sample and for the uniform sample. We compare the distribution of the areas of the Voronoi cells.

```
# first partition our galaxies
VSlist = list(x = VS$xproj, y = VS$yproj)
VStess = deldir(VSlist, rw = c(xmin, xmax, ymin, ymax))

# plot a subset (plotting all is not nice, there are too
many)
plot(VStess, xlim = c(2000, 2030), ylim = c(0, 30), wlines =
"tess", pch = ".",
    lty = "solid")
```



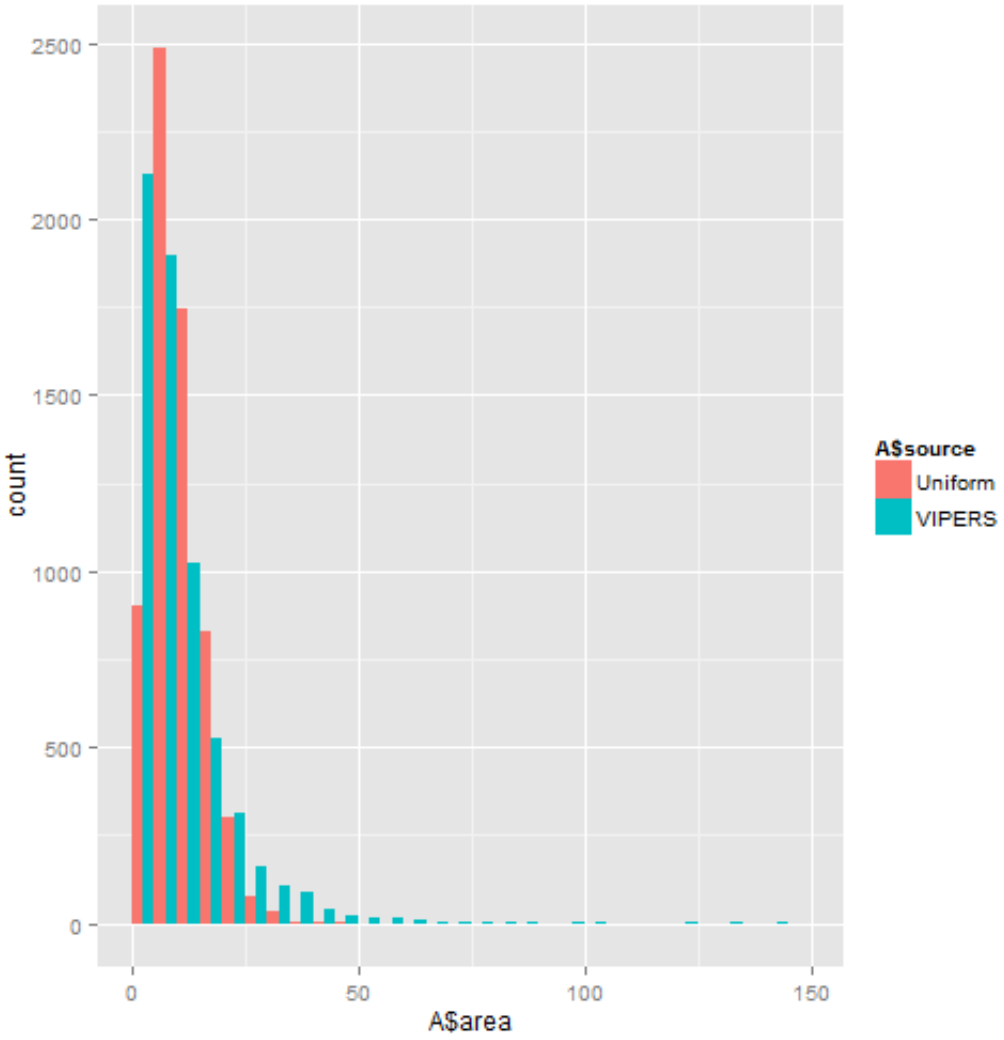
```
# then process the uniform random sample
Ulist = list(x = Udf$x, y = Udf$y)
Utess = deldir(Ulist, rw = c(xmin, xmax, ymin, ymax))

# obtain areas of the dirichlet cells
VSa = VStess$summary$dir.area
Ua = Utess$summary$dir.area

summary(VSa)
```

```
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
   0.15    3.95    7.41   10.60   13.30  242.00
```

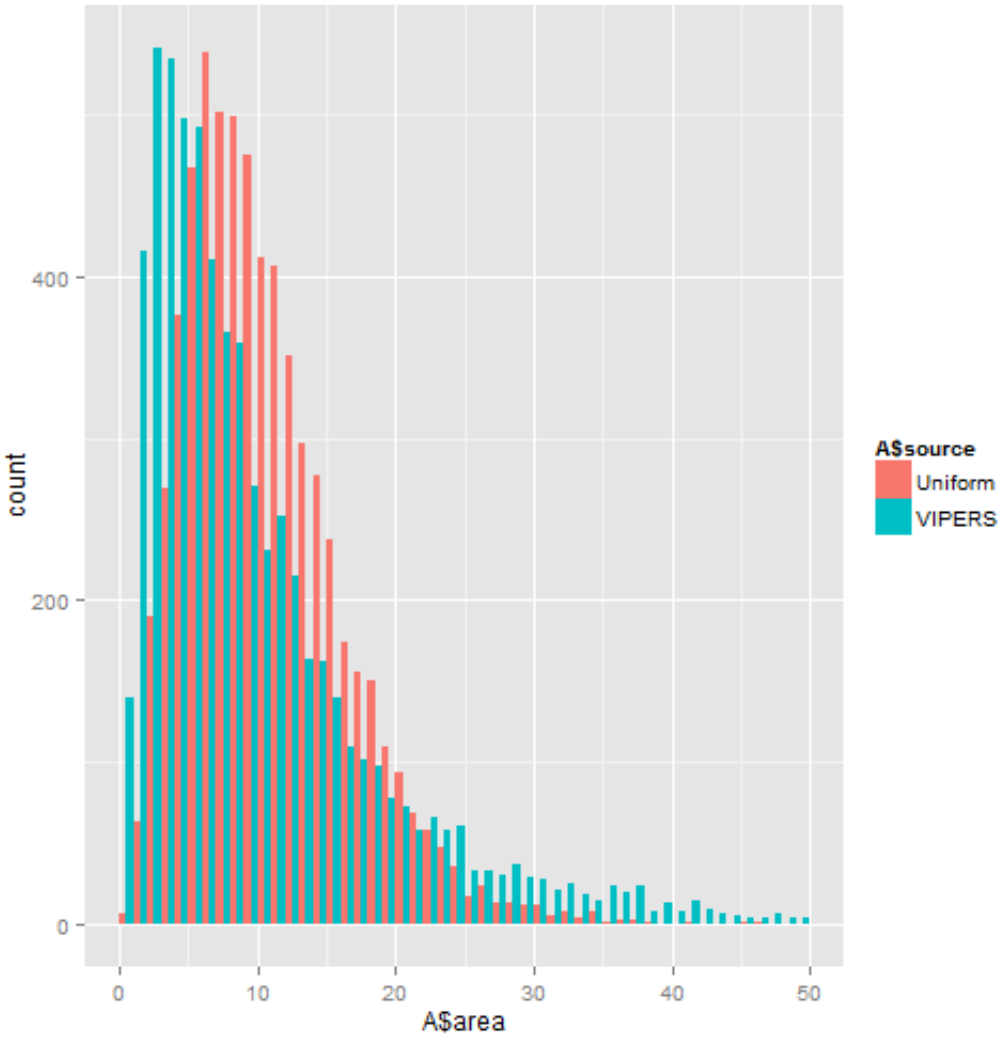
```
summary(Ua)
```

```
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
   0.41    6.45    9.57   10.60   13.70   46.60
```

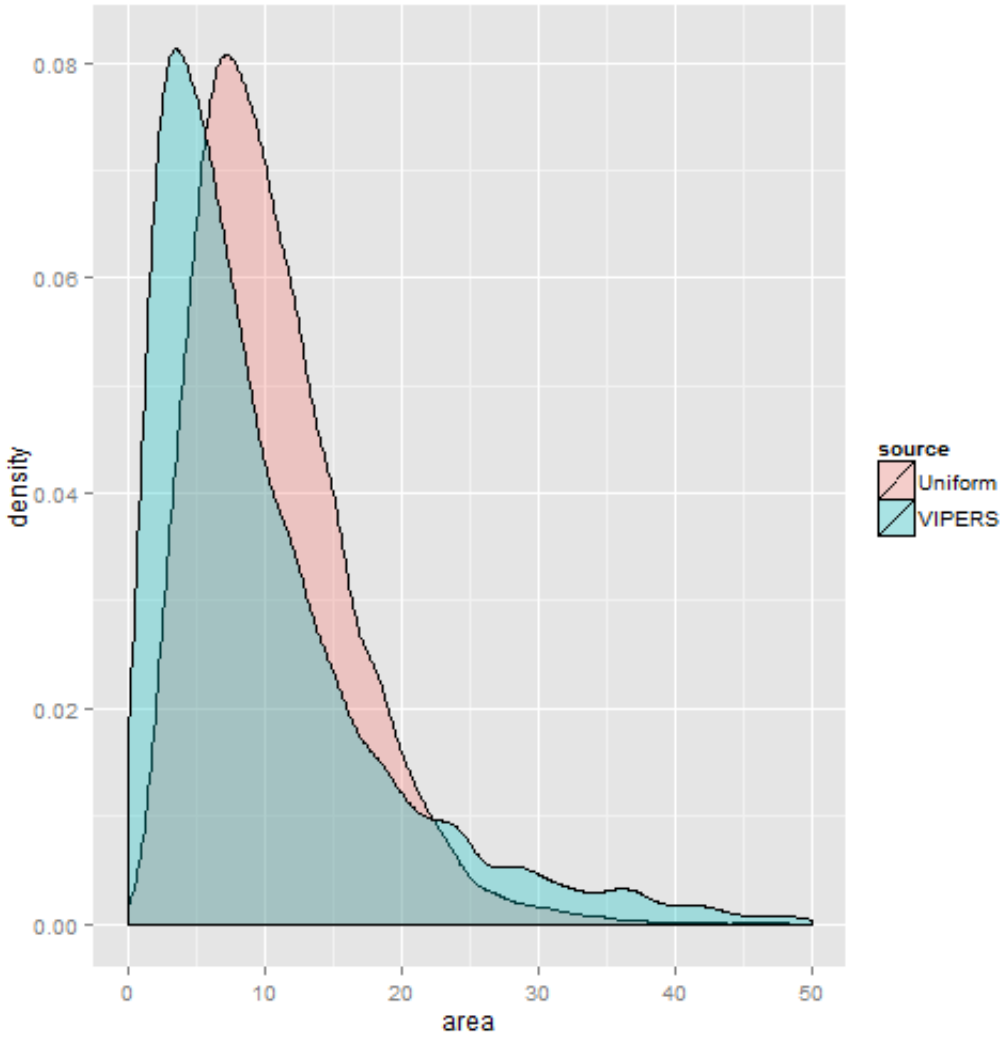
```
n = length(VSa)
A = data.frame(source = c(rep("VIPERS", n), rep("Uniform",
n)), area = c(VSa,
    Ua))

qplot(A$area, fill = A$source, position = "dodge", xlim =
c(0, 150), binwidth = 5)
```




```
qplot(A$area, fill = A$source, position = "dodge", xlim =
c(0, 50), binwidth = 1)
```




```
ggplot(A, aes(area, fill = source)) + geom_density(alpha =
0.3) + xlim(0, 50)
```



These results will be further discussed and expanded upon in future. For more details and future updates please refer to www.astrostatistics.org.