A Brief, Non-Comprehensive, Biased Introduction to Freely Available Spatial Statistical Software

Andrew Long

Department of Epidemiology, University of Michigan,
and BioMedware, Inc., Ann Arbor, MI 48104-1236, USA.

Abstract

Applications in the field of spatial statistics are increasing rapidly: more and more people are interested in incorporating space into their analyses rather than simply dichotomizing or otherwise simplifying the treatment of spatial information. GIS is leading this growth, in the sense that *access* to spatial information is pushing the demand for — and the development of — new techniques. While the major players of GIS (such as ArcView and MapInfo) are increasing our access to geo-referenced information, our appreciation of this newfound power must be tempored by the reality that many of the new users don't know much at all about spatial analysis: as Daniel Griffith has said, "... as the issue of computational intensity subsides, and GIS software becomes increasingly user-friendly, more ubiquitously available, and a source for implementing spatial statistical techniques, the danger of malpractice by the non-specialist practitioner grows[23]." We describe in this brief introduction a few of the freely available tools which interested users can count on to help them to get started.

We consider here only the "free" tools (rather than industry standards, which may cost upwards of $100,000). Many of these software packages are actually free; others are freely available (but the source code may be restricted); some of the software mentioned are available in demo versions. Free software usually comes with a price, however: either it is hard to install, not well supported, poorly documented, or has other problems. Because the goal of this paper is to indicate what is available today, and where (e.g. a URL), this paper should become quickly outdated: the only constant is change....

I. INTRODUCTION

Spatial Statistics

The field of spatial statistics encompasses many areas, such as point pattern analysis, exploration of spatial autocorrelation, spatial process modeling, autoregression, simulation of spatial random processes, local intensity estimation, and exploratory spatial data analysis[36,37,6,33]. It also includes geostatistical techniques, such as variogram and correlogram analysis, kriging cross-validation, and simulation [9,22].

Spatial analysis is now gaining in popularity, as it breaks out of traditional application areas such as ecology, meteorology, and mining and makes its way into areas such as epidemiology, archeology, environmental remediation and business. Correlated with that increase in interest is a desire to compute spatial statistics, and to carry out analyses of one's own modelled upon those found in the literature.

Of course there are expensive pieces of software to help one proceed, but what resources are available for those who operate on a shoe-string budget? This is the question we address here.

Computing Spatial Statistics

Can we all build spaceships? Obviously not. At one point in time, the aircraft industry was two guys in a bicycle shop in Dayton, OH: Wilber and Orville Wright had the state of the art in their hands. Now the state of the art is found at NASA, and it is unlikely that two guys working out of their home will ever challenge them.

Of course it is also the case that one person in a basement, working with today's technology and materials, can do a lot more than the Wright brothers ever dreamed of doing: model rockets are approaching outer space; individuals build helicopters in their garages.

The same thing happens in software. "While spatial statistics ought arguably to be at least as frequently taught and used as time series methods, it has been the case over many years that lack of access to such methods in statistics or GIS software has hindered diffusion."[5] So the little guys came, each building a small piece of software for performing a task of special interest. Each of these little pieces of software had its flaws - single platform, buggy, undocumented, memory-limited, speed-challenged, etc. - and so successive "generations" of software gardeners hoed and trenched and weeded until better software resulted.

1082-4006/99/0502-181$5.00

As better software results, commercially minded individuals begin to take notice: some add software procedures (taken from a pioneer's freely distributed code, since spruced up) to existing software, while others start from scratch and build up commercial applications around an interesting suite of functions that has been slowly growing. "Mission Critical" thinking leads to better code, improved by paid programmers whose jobs depend on doing good work; paying clients demand documentation, new routines, slicker interfaces, better import and export facilities, improved presentation options, and more functionality; and bugs are bad for business.

Like so the little guy is driven from the high-end market : never again can a single individual hope to compete with the ESRIs and Microsofts and other behemoths who feed millions upon millions of dollars into products for other little guys (and big corporate clients); but, like scraps of meat falling from the richly laden table, the little guy has better tools to use, better materials to play with, and better technology, and so continues to do things better (in small ways) than the monster-app builders - for a moment, which becomes briefer and briefer. We can no longer aspire to 15 minutes of fame, but only 7.5 minutes; and the duration drops exponentially with computer prices and inversely with hard disk size....

Thus, whereas in the early going it would have been hard to find commercial products to do the spatial analyses you need, and a list of software would have included Fortran, lisp, and basic code for working on mainframe VAXes and IBMs or Commodores and Apples, now we see a trend toward both stand-alone, commercial spatial statistical software and towards the development of modules or packages for doing spatial analysis within generic statistical or geographic software, with a dominant Windows influence (although linux may revive the UNIX market).

The brilliant French mathematician Poincare[1] was said to be the last mathematician to hold all of mathematics in his head. We are now at the stage where perhaps no one can keep tabs on all the products - commercial, freely distributable, or public domain - which exist to facilitate spatial analysis. This is due to size and dynamics: the list is constantly changing, and growing: old software falls out of favor, new software is born; software matures, goes commercial, etc. "Chaotic dynamics" is a good analogy for those seeking to stay up with any analysis tools: this flux is enough to drive one mad. How to stay current?

One individual striving to keep us all sane and current is Grégoire Dubois, who runs a web site on spatial statistical software[16]. Dubois has done a lot in this area, including establishing the AI-GEOSTATS list serve[2]. His AI-GEOSTATS home page[15] has job listings; bibliographies; a searchable web version of the mailing list; news of conferences, courses, etc. In sum, this site is a must-stop on one's trip through spatial analysis.

Repositories of software, information, etc. are another important source for free and public domain software. It is helpful to know a starting point for searches. One important aid for those seeking is StatLib[12], a major distributor of statistical software, datasets, and information by email, ftp, and the world wide web. Similar repositories exist for GNU software[32] and for TEX-related software[7]. Any one of us seeking to find software should snoop around there; those seeking to create software to share with other uses should certainly make use of this type of repository: it forces better management of your resources.

II. GEOGRAPHIC INFORMATION SYSTEMS

Anyone working with spatial data will recognize the value of a geograhic information systems(GIS): it is the perfect platform for the management and analysis system for spatial data. It is fairly safe to say that the ordinary user today is a Windows user, which means that to be competitive and to have a product worth attention, it is essential to put it on this platform of choice. Unfortunately, however, there is no good, free Windows GIS available.

Geographic Resources Analysis Support System

The only good, free, relatively full-featured GIS is Geographic Resources Analysis Support System (GRASS)[4], which is available on UNIX platforms (including linux). I have been surprised by the number of people who, while professing to be knowledgeable about GIS, don't know about GRASS. GRASS is the granddaddy of GIS, originally developed and maintained by the US Army CERL. CERL dropped support for the public domain project, however, as government agencies out-sourced their GIS needs; GRASS languished as a result.

The Center for Applied Geographic and Spatial Research at Baylor University has recently assumed management of GRASS: "CAGSR is the official home of the GRASS GIS, a powerful raster-based GIS originally developed by the U.S. Army Corps Of Engineers.

[1] Jules Henri Poincare, b. Apr. 29, 1854, d. July 17, 1912. "He is often described as the last universalist in mathematics....Poincare was first to consider the possibility of chaos in a deterministic system, in his work on planetary orbits. Little interest was shown in this work until the modern study of chaotic dynamics began in 1963."[27]

[2] To become a member, send email to majordomo@gis.psu.edu with no subject and "subscribe ai-geostats" in the message body.

CAGSR scientists update and maintain GRASS, as well as use it in projects and research and development activities." Is this the beginning of a GRASS renaissance?

In terms of spatial analysis, GRASS has rudementary support. GRASS provides some limited functionality for spatial statistics, usually via contributed packages (some of which do not come with the default distribution). I've used it for creating Dirichlet tesselations (Theissen polygons, Voronoi diagrams), as well as for computing contiguity matrices, Moran's I, etc. GRASS is essentially a huge collection of small codes (e.g. v.autocorr - for computing spatial autocorrelation statistics for areas), many written by a single author in the GRASS style. As a user needs a routine, s/he writes it; when it gets standardized it may be incorporated into the distribution.

This illustrates the first type of "extension" or "module" we will encounter here: a piece of code provided by a user, group, or company. GRASS does not make it particularly easy to add routines of one's own to its pantheon (so that others may use one's code as well): as in all things GRASS, one must rummage around the documentation department for the keys for doing so. But the keys are there, someplace!

GRASS is community software, relying on a community of excited, interested users to keep it alive and vibrant; and GRASS has suffered a setback in recent years. The next few years will determine whether it dies entirely or if the folks at Baylor can manage to revive it. Certainly GRASS is now easier to install: I recently installed it on UNIX and linux systems with only minimal effort; it includes a GUI (Graphical User Interface) which makes it easier than ever to use; and the home page provides enough assistance to get one started. Pre-compiled binaries are available for those without compilers or averse to compiling programs.

ArcView

While ESRI's ArcView GIS is not free, I mention it for several reasons:

- there is no good freely available GIS in the Windows environment,
- it is extremely popular,
- the ArcView system shows how free software may come on-line in commercial modern computer systems.

Several colleagues and I in the department of Epidemiology at the University of Michigan have been using ArcView in a course on spatial epidemiology for about a year. Our experience so far has been very positive. The software is complicated (there are many, many speed buttons), and limited in certain important ways (especially file import and export, certainly in terms of spatial analysis functionality), but the students took to it well and were able to carry out some nice projects using it.

Unfortunately however, there are few spatial statistical features available within ArcView (natively). There is a growing and substantial collection of extensions which are providing ArcView with the potential to be a serious contender for the foundation of one of the best spatial analysis tools available. Many of these extensions are freely available (and will no doubt remain so until ESRI standardizes them and incorporates them into their software).

ESRI has made the development of extensions easy, a very intelligent marketing and development model: unlike GRASS, it is simple to create and add an extension in ArcView, increasing flexibility and augmenting the power of ArcView. It is a win-win situation for users and developers.

The biggest problem with ArcView is that it costs an arm and a leg (for most of us, anyway). Thus, while some tools may be free, the electricity necessary to run them is not. A 30-day demo CD of ArcView is available from ESRI.

III. BASIC SPATIAL STATISTICAL PACKAGES

Many of us have need of spatial statistics like Moran's I, Local Indicators of Spatial Autocorrelation, BW statistics, scan statistics, etc. These statistics are computed by many different packages, from stand-alones to extensions or modules.

Let's have a brief look at one commercial software product, so that we can compare what's being done for cash to what can be done for free. S-Plus has become a leader in the spatial statistical field, due as much to the contributed code of its devoted users as to its own code. For example, S+geostats[28] is designed by its authors to " implement a set of exploratory and modeling tools for geostatistical data". S-Plus is thus another corporate subscriber to the philosophy that it is in the best interest of the company to please an army of smart, excited people working for free.

S-Plus, like many popular software packages, has also benefited from the publication of textbooks designed for the simultaneous job of teaching statistics via (or at least hand-in-glove with) the package (e.g. Venables and Ripley[39]). This text implements many of the standard point pattern analysis routines, such as

Ripley's K-function, sequential inhibition process simulation, etc., as well as some geostatistical functionality (kriging, variogram modelling).

What can you get for free?

The R language[1] (also known as GNU S) does a good impression of S-Plus (see Ross Ihaka's history of R[24]. Both are based on the S language, originally developed by AT&T's Bell Laboratories. Roger Bivand and Albrecht Gebhardt's[5] provide a description of the R language facilities for spatial statistics and geostatistics called "Implementing functions for spatial statistical analysis using the R language". This is a good place to start. According to these authors, "....functions for three types of spatial statistics are covered: spatially continuous data, point pattern data, and area data." Albrecht Gebhardt has released an R version of S+Geostats[20], which contains much of the functionality of the original version.

Venables and Ripley produced an R companion for their book "Modern Applied Statistics with S-Plus"[40], which serves to illustrate the seriousness of R's challenge to S-Plus. As fast as S-Plus can introduce a new package for analysis, there is a group of statisticians working to duplicate the work and incorporate it into the R pantheon.

R has also followed S-Plus in making the creation of new extensions ("packages") relatively painless [40]. R is also fairly painless to install, and has an active users group on the web which is quick to help the fledgling with those crucial first steps (even when the fledgling fails to read the documentation...).

Xlisp-Stat[35] is a package somewhat similar to R, in that it is available in the three most popular flavors of operating systems (UNIX, Windows, and Mac), has a strong user base, and is free and easily extensible. There are several add-ons for doing geostatistical and spatial statistical analysis available from the UCLA Xlisp-Stat repository[10]. LiveMap is an extension which provides limited GIS functionality (even going beyond standard GIS functionality at times: linked plots, for example).

Not only are Xlisp-Stat and R free, but they're available to everyone with either a Mac, a PC, or a UNIX box. Of course you can't (for the moment) do as much with such a package as you can with S-Plus, SAS, or other high powered (and high priced) systems, but if all the geniuses spending their spare hours writing code for commercial vendors without compensation turned their attention to one good public domain package, we'd soon follow our noses to the success that the GNU software and Linux model have enjoyed.

Art Getis and DongMei Chen of San Diego State University have created a package which they call PPA (Point Pattern Analysis)[21] available for Windows and UNIX. As the name implies, it provides support for many of the standard point pattern analyses, including Ripley's K-functions, Moran's I, Geary's c, nearest neighbor analysis, etc. This is one of the old-fashioned software packages for computing spatial statistics: no-nonsense, it features a short and sweet user manual, but no extensibility, no tutorials, no frills; just the power to compute, with some confidence that the answers will be right if the user knows enough to give the right inputs.

To give an example of a free and friendly, small, standalone package, consider Martin Kulldorf's Program SaTScan[25]. It purports to do the following: "The SaTScan software analyses spatial, temporal and space-time point data using the spatial, temporal, or space-time scan statistic. It is designed for any of the following interrelated purposes:

- To evaluate reported spatial or space-time disease clusters, to see if they are statistically significant.
- To test whether a disease is randomly distributed over space or over time or over space and time.
- To perform geographical surveillance of disease, to detect areas of significantly high or low rates."

SatScan is free, easy to install, and includes examples.

Some Interesting Extensions

Luc Anselin's SpaceStat web page[2] includes a link to a free extension for ArcView which I found very useful, even if I don't own SpaceStat! It derives the rook/queen's contiguity relationship from an area map, and produces a file of centroids of subregions of an area map (reporting as a limiting case the coordinates of a point file). One would think that both of these functions should be straightforward and included in ArcView, but they are not (yet, although the latter is an example script). Presumably linking SpaceStat to this extension makes it even better!

"Spatial Tools[38] is an ArcView extension that contains a collection of 19 tools that extend the capabilities of Spatial Analyst. The majority of tools are implementations of functions available in spatial analyst from avenue programming or awkwardly in the map calculator but not from the menu, button, or tool interface. These include functions to clean up, assemble, aggregate, warp and analyze grids."

Cook, et al.[8] have linked XGobi[34] to ArcView in a UNIX-based extension. It looks really marvellous, and is free from their web site. It allows for linked plots: for example, clicking on a point in a data set illuminates all points in the variogram cloud deriving from that point. XGobi itself is a very useful package for exploratory spatial data analysis. Brian Ripley has ported XGobi to Windows (although it still requires an X-Window server under Windows). Both S-Plus and R provide a function which allows one to use XGobi from within them, allowing for data spinning, high-dimensional plotting, linked plots, etc.

IV. GEOSTATISTICAL PACKAGES

The reader would do well to visit Dubois's site[16] for more details on most of the following software packages. He gives more details there than we can give here, and he'll be keeping them more up-to-date[3].

- Geo-EAS[4][17] (Geostatistical Environmental Assessment Software) is a dinosaur - but a friendly dinosaur, which still might prove useful in a pinch. It is freely available in UNIX and DOS versions (although the UNIX version contains certain features - e.g. postscript plots, automated variogram modeling - which make it somewhat more useful, especially with the beginner).

  The DOS version is fairly easy to get up and running; the UNIX version is somewhat more complicated, although I think that the installation instructions should get one through the process. I currently run the Home Page, and provide some support (as the person who ported it to UNIX).

  Many people could get by with Geo-EAS. It handles moderately large problems, and provides the following functionality: variogram modeling, kriging, cross-variogram modeling, cokriging, cross-validation, simulation, and the associated (and I think necessary) visualizations. This is a minimal suite of spatial interpolation and simulation functions[5], one might call this the essential geostatistical core. Most packages provide this core suite, although cokriging and simulation have tended to be somewhat optional.
- Gstat[30] is another geostatistics package available for UNIX and Windows, written by E.J Pebesma and available for download[29]. Grégoire Dubois writes "for more advanced work, I can only recommend ... Gstat (free, codes available, running under Dos or UNIX), an advanced geostats package with [much] functionality and very well documented. Very professional work." An on-line manual is available from the web site.

  This package uses freeware Gnuplot[11] as a graphing device, and it permits graphical output as gifs, postscript, etc. Gnuplot has very nice graphics, which makes for a good marriage with Gstat; but it must be installed separately, of course. I had a small amount of difficulty with the Gstat install, but found it to be friendly enough once it was in place.
- "GSLIB[14] is an acronym for Geostatistical Software LIBrary. This name was originally used for a collection of geostatistical programs developed at Stanford University over the last 15 years."[13] GSLIB has Windows and UNIX versions. I've tried both, and the examples work well enough (although I haven't used it for my own work). Rather than being an interactive package, it relies on command files.

  The newest edition of the book "GSLIB: Geostatistical Software Library and User's Guide"[13] comes with new code, written in Fortran90. I haven't tried that yet, but the old GSLIB produces postscript plots which can be very nice (e.g. color raster images). GSLIB includes code for variogram-fitting, kriging, cross-validation, simulation, etc.
- I'll mention one commercial package, which I've used personally and like to use in the classroom. GS+[19] is a commercial product which does simple geostatistical analysis simply. They have a free demo-version available from their web-site, which allows one to get a good idea of what it can do (some functionality - not much, really - is disabled). I found this to be a friendly package, which my students could use very easily. It is a good introductory software package, including automatic variogram fitting and anisotropy analysis.

There are obviously many, many software packages which I have neglected to mention (and which undoubtably deserve mention). The one I'm most eager to try myself is probably UNCERT[41], which is touted as "A Geostatistical Uncertainty Analysis Package Applied to Groundwater Flow and Contaminant Transport Modeling".

V. WEB COURSES

For the interested reader, here are some web-based courses which hold varying amounts of interest for this who want to learn more about spatial statistics.

Quantitative Spatial Statistics[31] at Colorado State is one course with useful portions on the web (including a mammoth Course Manual in pdf format). They use S-Plus.

Graphical Data Analysis[3] at the University of Montana has much detail on-line, and focuses on R, S-Plus, and Xlisp-Stat.

[3] Provided that his site continues to operate....

[4] This is a horrible name, which needs to be simplified! I usually write it as "geoeas".

[5] The simulation and cokriging functions were added by the Geostatistics Group at the University of Arizona and not part of the original distribution.

Our course, The Spatial Analysis of Disease Patterns[26] concerns applications of spatial statistics in public health in an essential way. We have much information available at our site, including on-line lectures, labs, software, and other resources for those interested in spatial statistics.

We treat lots of different pieces of software, including ArcView, GRASS, Stat!, Geo-EAS, GS+, S-Plus, R, Xlisp-Stat, XGobi, and more. We alternate between UNIX and Windows software. Our goal is to use appropriate software for the situation discussed, rather than to use a single piece of software (however inappropriate).

For those interested in learning more about GIS and ArcView, the ESRI Virtual Campus[18] may hold some allure. You might have a look at it just to see a good model of what will undoubtably be done much more in the future.

VI. CONCLUSION

We have seen that there is much spatial statistical software available for free; the question is how much work do you want/have to do to get it up and running? Most folks don't want to do <u>any</u> work to get started! The disadvantages of freeware are many: start with minimal support (perhaps the email address of an author); throw in sometimes poor documentation or strange GUI; add difficulties in installation. These problems have resulted in limited use, mainly by those who are already proficient in programming and operating systems (and so who are not easily put off by multiple compilation errors, configuration problems, etc.).

One of the success stories in this department is R, which is a valuable and realistic alternative to S-Plus. It is becoming increasingly easy to install and work with, and includes many important types of analyses (including point pattern analysis, spatial process modeling, and geostatistical techniques). Beautiful and complex visualization routines are one of the characteristics that distinguish R from the rest of the field.

Other software packages and programs offer bits and pieces of the spatial statistical pantheon: PPA does routine point pattern analysis; SatScan detects clustering; Xlisp-Stat offers a small subset of the usual GIS functionality. Unfortunately, however, these packages are not designed to come together ultimately, but are destined to remain separate pieces of software, fundamentally different in design.

Many challenges remain for freely available spatial statistical software. To cite a few:

- Software must be easily extensible (e.g. ArcView/ S-Plus models of extensibility). R is managing this.
- Software must cross platforms: the fact that there is no good public domain or freely available GIS for the Windows platform is a serious void. R has succeeded here;GRASS has not, and the lack of a good Windows platform GIS is a serious blow to the free spatial stats arena.
  UNIX software (e.g. GRASS) can remain a vibrant and important product, depending crucially on the success of the Linux experiment. If Linux succeeds, then the creation of simple to install rpm packages means that even complex software packages can be installed simply and easily. At that point, the GUI and power of the software become the limiting factors (rather than installation headaches!).
- Software must remain up to date: this is usually not a problem, as advances in software generally come from outside of software companies, and so must be implemented "the old fashioned ways", before being sucked up by software firms.
- Documentation and tutorials must be improved and expanded, to allow for easy installation and use by the ordinary user. Similar sentiments apply to the GUI, which must be friendly enough that users will not be frustrated and aggravated to the point of putting the program aside.
- Finally, the code itself must be reliable. Users can improve the code, of course, by testing it themselves and locating bugs early. Free and freely available software must be a team effort! It depends on an active and helpful users group.

As already noted, free and freely available spatial statistical software will always be around: the extension models of software giants like ESRI and MathSoft guarantee it, and historical precedent says that, as long as there are programming languages and active minds, there will be programmers seeking to solve problems in new and unprecedented ways.

What is the ultimate role of free software? That's the most interesting question, and one which we cannot yet foresee clearly. The answer is fundamentally linked to issues such as the near-monopoly of the Windows operating system, the success of the Linux model, the GIS marketplace, and other issues which are as yet unclear. As Linus Torvalds (creator of Linux) and Donald Knuth (creator of the $\TeX$ typesetting system) have demonstrated, one person can make a major (and unexpected) difference; and a system where one person can turn everything on its head is not very stable. One thing is sure, however: for the moment much good quality, freely available spatial statistical software is available for the taking.

REFERENCES

[1] *The Comprehensive R Archive Network*, 1999. http://lib.stat.cmu.edu/R/CRAN/.

[2] L. Anselin, 1999. *SpaceStat*. http://www.spacestat.com/ http://curie.ei.jrc.it/software/spacestat.htm.

[3] J. Banfield, 1999. *Statistics 438: Graphical Data Analysis. University of Montana*, http://www.math.montana.edu/~umsfjban/Courses/Stat438/.

[4] Baylor University, 1999. http://www.baylor.edu/~grass, *GRASS Home Page*.

[5] R. Bivand and A. Gebhardt. 1998. *Implementing Functions for Spatial Statistical Analysis using the R Language*, http://www-stat.uni-klu.ac.at/~agebhard/ERSA-98-D8-427/.

[6] A.D. Cliff and J.K. Ord. 1981. *Spatial Processes: models and applications*, Pion Limited, London.

[7] *Comprehensive TeX Archive Network*,1999. http://www.ctan.org/.

[8] D. Cook, 1999. *Xgobi extension to UNIX ArcView*. http://www.public.iastate.edu~arcview-xgobi/.

[9] N. A. Cressie, 1991. *Statistics for Spatial Data*. Wiley, New York.

[10] J.de Leeuw, 1999. *UCLA Xlisp-Stat Archive*, http://www.stat.ucla.edu/develop/lisp/xlisp/xlisp-stat/.

[11] Department of Computer Science, Dartmouth College, 1999. http://www.cs.dartmouth.edu/gnuplot/_info.html. *Gnuplot Home Page*.

[12] Department of Statistics, Carnegie Mellon University,1999. http://lib.stat.cmu.edu/. *StatLib software, Dataset, Information Distribution System*.

[13] C. Deutsch and A. Journel. 1998. GSLIB: *Geostatistical Software Library and User's Guide*. Oxford University Press, 2nd edition.

[14] C. Deutsch and A. Journel. 1999.*Geostatistical Software Library*. Stanford University, http://ekofisk. stanford.edu/scrf/software.html, http://www.gslib.com.

[15] G. Dubois, 1999. *AI-GEOSTATS Home Page*.http://curie.ei.jrc.it/ai-geostats.htm.

[16] G. Dubois, 1999. *AI-GEOSTATS Software Index*. http://curie.ei.jrc.it/software/index.htm.

[17] E. Englund and A. Sparks. 1999. *GEOstatistical Environmental Assessment Software*. Environmental Protection Agency EPA-EMSL, Las Vegas USA.,http://www.sph.umich.edu/~aelon/geoeas/.

[18] Environmental Systems Research Institute, Inc., 1999. http://campus.esri.com/. *ESRI Campus*.

[19] Gamma Design, 1999. http://www.gammadesign.com/. *GS+ Home Page*.

[20] A. Gebhardt., 1999. *S+geostats Home Page(R Version)*. http://www-stat.uni-klu.ac.at/~agebhard/ERSA-98-D8-427/node1.html.

[21] A. Getis and D. Chen. 1999. *PPA (Point Pattern Analysis)*, http://xerxes.sph.umich.edu:2000/cgi-bin/cgi-tcl-examples/generic/ppa.cgi.

[22] P. Goovaerts, 1997. *Geostatistics for Natural Resources Evaluation, Applied Geostatistics Series*, Oxford University Press.

[23] D. Griffith, 1996. *Practical Handbook of Spatial Statistics*, CRC Press.

[24] R. Ihaka, 1999. *History of the R language*. http://www.ci.tuwien.ac.at/R/doc/html/interface98-paper/paper.html.

[25] M. Kulldorff, K. Rand, G. Gherman, G. Williams, and D. DeFrancesco. 1999. *SaTScan: Software for Calculating the Spatial, Temporal and Space-Time Scan Statistics*. National Cancer Institute Division of Cancer Prevention, http://www.dcpc.nci.nih.gov/BB/SaTScan.html.

[26] A. Long, G. Jacquez, M. Wilson, and L. Estberg. 1999. *GeoMed Home Page*. BioMedware, Inc. and The University of Michigan, http://www.sph.umich.edu/geomed/

[27] The MacTutor History of Mathematics archive, 1996. http://www-groups.dcs.st-and.ac.uk./~history/Mathematicians/Poincare.html. Jules Henri Poincaré.

[28] J.J. Majure, 1999. *S+geostats Home Page*. Iowa State University,http://www.gis.iastate.edu/SGeoStat/homepage.html.

[29] E.J. Pebesma, 1999. *Gstat Home Page*. http://www.frw.ruu.nl/gstat/.

[30] E.J. Pebesma and C.G. Wesseling. 1998. *Gstat: a program for geostatistical modelling, prediction and simulation.Computers & Geosciences*,24(1):17—31.

[31] R. Reich and R. Davis. 1997. *Quantitative Spatial Statistics NR/ST 523*, Colorado State University, http://www.stat.colostate.edu/~rdavis/st523/.

[32]Richard Stallman, et al.1999. *GNU's Not UNIX*, Free Software Foundation, http://www.gnu.org/.

[33] B.D. Ripley, 1981. *Spatial statistics*,Wiley.

[34] D.F. Swayne, D. Cook, and A. Buja. 1999. *XGobi: a system for multivariate data visualization*. http://www.research.att.com/~andreas/xgobi/.

[35] L. Tierney, 1998. *Lisp-Stat Information*. http://stat.umn.edu/~luke/xls/xlsinfo/xlsinfo.html.

[36] G. Upton and B. Fingleton. 1985. *Spatial Data Analysis by Example: Point Pattern and Quantitative Data* 1, Wiley.

[37] G. Upton and B. Fingleton. 1989. *Spatial Data Analysis by Example: Categorical and Directional Data* 2, Wiley.

[38] U.S. Geological Survey, Anchorage, AK, USA; 1999. *GIS Tools*.http://www.absc.usgs.gov/glba/gistools/.

[39] W.N. Venables and B.D. Ripley. 1994. *Modern Applied Statistics with S-PLUS. Statistics and Computing*. Springer-Verlag, New York.

[40] W.N. Venables and B.D. Ripley. 1999. *R Complements to Modern Applied Statistics with S-Plus*. http://www.stats.ox.ac.uk/pub/MASS2/VR2R.pdf.

[41] W. L. Wingle, E. P. Poeter, and S. A. McKenna. 1997.*A Geostatistical Uncertainty Analysis Package Applied to Groundwater Flow and Contaminant Transport Modeling*, Department of Geology and Geological Engineering, Colorado School of Mines, http://uncert.mines.edu/