EXPLORATION OF SATELLITE IMAGES IN THE DYNAMICALLY LINKED ARCVIEW/XGOBI/XPLORE ENVIRONMENT[1]

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ABSTRACT

The dynamic link among the Geographic Information System (GIS) ArcView, the dynamic statistical graphics (DSG) program XGobi, and the statistical computing environment XploRe has been successfully used to explore and analyze all kinds of spatially referenced data — from forest health data over precipitation data to precision agricultural data. In this paper, we will focus on the exploration of satellite images using the linked ArcView/XGobi/XploRe software environment.

INTRODUCTION

Multispectral satellite image data, i. e., remote sensing data gathered through earth observation satellites attracted the attention of statisticians working in the field of dynamic statistical graphics (DSG) during the last decade. Many prototypes of software systems have been developed over time that focus on many interesting software features but yet lack the full functionality that is required to geographically explore satellite images.

The ArcView/XGobi/XploRe software environment consists of the Geographic Information System (GIS) ArcView 3.0^{TM}, the dynamic statistical graphics (DSG) program XGobi [25], and the statistical computing environment XploRe [13]. These three programs, linked together into one single environment, provide features such as linked brushing among multiple windows of different types (e. g., map views and statistical plots), grand tour [1], [2], projection pursuit guided tour [6], and standard clustering and classification methods, that are very powerful when jointly used for the exploration and classification of satellite images.

In the following sections we will look at examples from the literature where satellite images have been analyzed using dynamic statistical graphics. We describe the ArcView/XGobi/XploRe software environment, and we explain how it can be used for remote sensing data. We finish with a discussion and an overview on future directions.

SATELLITE IMAGES AND DSG

Various statistical methods have been developed for the classification of remote sensing imagery. Many of these methods are based on principal components and are widely used in the remote sensing community for non–supervised classification purposes. Other statistical approaches that are also well–acknowledged in the remote sensing community have been focused on the optimum band selection for supervised classification. However, most of these solutions ignore the visual capabilities of human beings, highly depend on probably incorrect ground truth, or omit potentially valuable information at an early stage of the analysis.

Exploration of satellite images via DSG is mostly based on human interaction and visual capabilities. This approach helps to detect incorrect ground truth and it does not ignore any of the information that is available. Unfortunately, there exist only experimental software solutions within the statistical community so far that support this approach. Some examples of the exploration of satellite images through DSG follow.

In [4], a Landsat 2 multispectral scanner (MSS) image of the confluence of the Rio Solimões and the Rio Negro near Manaus, Brazil, has been considered. The authors use the Data Viewer [3], [14], a program for the graphical data analysis, to explore the four–dimensional spectral data. The authors are capable to graphically confirm (through linked brushing and the grand tour) that the measurements on a transect across

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[1] Approved for public release; distribution is unlimited.
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the confluence (mixing) of the two rivers can be represented as a convex combination of the corresponding two water spectra. An earlier video [19] provides more details of this analysis.

In [15], the simple image program MTID and XGobi have been linked together. The authors analyze Landsat Thematic Mapper (TM) images of the agricultural Paraná State region. Based on their graphical analysis, a discrepancy between the images and the ground truth becomes immediately obvious. Probably a shift of the recorded ground truth in relation to the images has occurred.

Scott [23] considers four–channel MSS data from NASA's Landsat IV satellite, taken from an agricultural scene in North Dakota on 5 different days in 1977. Scott displays trivariate scatterplots and contours of the transformed 20–dimensional data and he finds clusters that clearly discriminate between sunflowers and small grains.

Salch and Scott [21] demonstrate a 2–dimensional density grand tour of a Landsat satellite image based on three groups of farm crops. The density grand tour reveals that at least one of the crops contributes to the multimodality of the densities. This is a feature that is also detected in other agricultural settings if one (or more) crop(s) has been planted at different points in time, thus yielding a wide variety of the underlying spectral measurements.

Finally, Carr [5] presents a hexagon bin scatterplot matrix based on the seven spectral bands of a Landsat image at a Nevada test site. This binned scatterplot matrix shows areas of high and low concentrations of numbers of pairs of the seven spectral bands, almost perfect linear relationships between several pairs of bands, a cutoff of intensity values for the thermal band, and bivariate outliers.

Unfortunately, in the last two examples the statistical plots are not directly linked to the original satellite image. Therefore, no immediate geographic conclusion can be drawn from the graphical statistical exploration of the data.

THE ARCVIEW/XGOBI/XPLORE ENVIRONMENT

The ArcView/XGobi/XploRe environment is a software environment where the Geographic Information System (GIS) ArcView 3.0, the dynamic statistical graphics (DSG) program XGobi [25], and the statistical computing environment XploRe [13] have been linked together, thus providing us with three different main concepts in one single environment. We can (1) display spatial locations ans concomitant variables on maps, (2) visualize these concomitant variables using interactively manipulated dynamic statistical graphics, and (3) conduct numerical statistical analyses. While ArcView's strengths are in (1) but it merely supports (2) and (3), XGobi's and XploRe's strengths are in (2) and (3), respectively. A link between these three programs does not only provide the sum of the features of the underlying programs but, in addition, we can gain further insight and understanding of our data through interaction and dynamic linking among the programs. See [27] and [26] for technical details of the software environment and possible applications for spatial data analysis such as real estate data and precision agricultural data.

Remote Procedure Calls (RPCs) are the underlying Interprocess Communication (IPC) mechanism used for the communication among the three programs. More details on this IPC technology can be found in [24] and [9].

In addition to the publications on the entire ArcView/XGobi/XploRe environment, there exist several articles that focus on the preliminary ArcView/XGobi link. A description of the main features of this link (multivariate data, spatial cumulative distribution functions, variogram–cloud plots, spatially lagged scatterplots, and multivariate variogram–cloud plots) and examples that range from forest health data over precipitation data to satellite images can be found in [7] and [8], for example. In [31], a comprehensive summary on the technical details of the ArcView/XGobi link has been given. However, what has been stated there still holds for the entire ArcView/XGobi/XploRe environment. Recent developments on XploRe can be found in [17], [18], and [22].

EXPLORATION OF SATELLITE IMAGES THROUGH ARCVIEW/XGOBI/XPLORE

In this section, we look at three different examples of remote sensing imagery. The first two examples only make use of the ArcView/XGobi link and have been described in more detail in [29] and [30] (Example 1) and [7] (Example 2). Example 3 is based on data presented in [11] and [12] and makes use of the full ArcView/XGobi/XploRe environment.

EXAMPLE 1: LAKE ICARIA WATERSHED

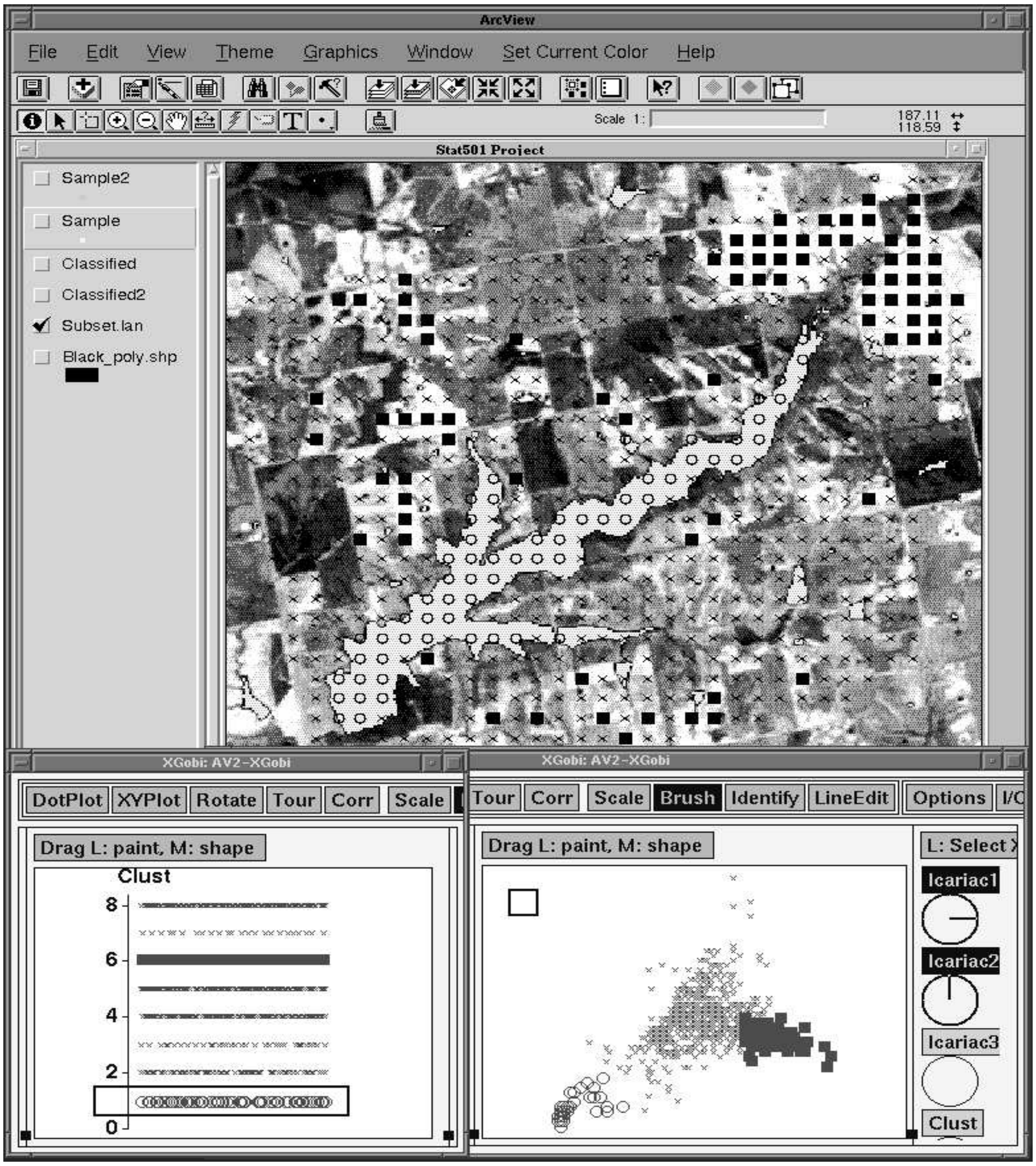

Figure 1: *The ArcView map view (top) is linked with two XGobi views (bottom). The left XGobi shows the 7 clusters obtained from a hierarchical cluster analysis. The right XGobi shows a scatterplot of the variables Icariac1 and Icariac2. The two clusters brushed in the left XGobi fall on lake locations (circles) or areas with active vegetation (filled boxes) in the ArcView map view. They also form two of the corners of the data triangle in the right XGobi.*

This example shows three ranges of wavelengths of electromagnetic radiation (expressed through the variables *Icariac1*, *Icariac2*, and *Icariac3*) measured on April 22, 1990, by the SPOT earth observation satellite. The area under consideration relates to the Lake Icaria watershed in southwest Iowa (near Corning). Instead of using all 300,000 pixels of the scene that are available in ArcView, we took a systematic random sample (e. g., [10], Section 5.6.1) of 800 locations for further analysis in XGobi.

At the time we analyzed this data, XploRe was not yet accessible through a link. It took the user five individual steps to create a new variable *Clust* that contains the result of a hierarchical cluster analysis.

To ease the access to analytical statistical methods we decided to add XploRe to the ArcView/XGobi link. Today, within the ArcView/XGobi/XploRe environment, these steps could be done by pressing a few buttons in ArcView to activate the required functionality within the other two programs.

Figure 1 (a reprint from [29] and [30]) shows the ArcView view (top) and two XGobi views (bottom). We brushed two of the clusters in the dotplot of *Clust* (left XGobi). We see that these clusters are two of the corners of the data triangle in the scatterplot of the variables *Icariac1* and *Icariac2* (right XGobi). In the ArcView view, these points fall on lake locations (circles) or areas with active vegetation (filled boxes). The next step of our interactive analysis might have been the brushing of the third corner of the data triangle in the right XGobi to see if these points also relate to a particular geographic region in the map view. An accompanying video [28] gives additional insight into this interactive and dynamic analysis.

EXAMPLE 2: BORDER REGION BETWEEN VERMONT AND NEW HAMPSHIRE

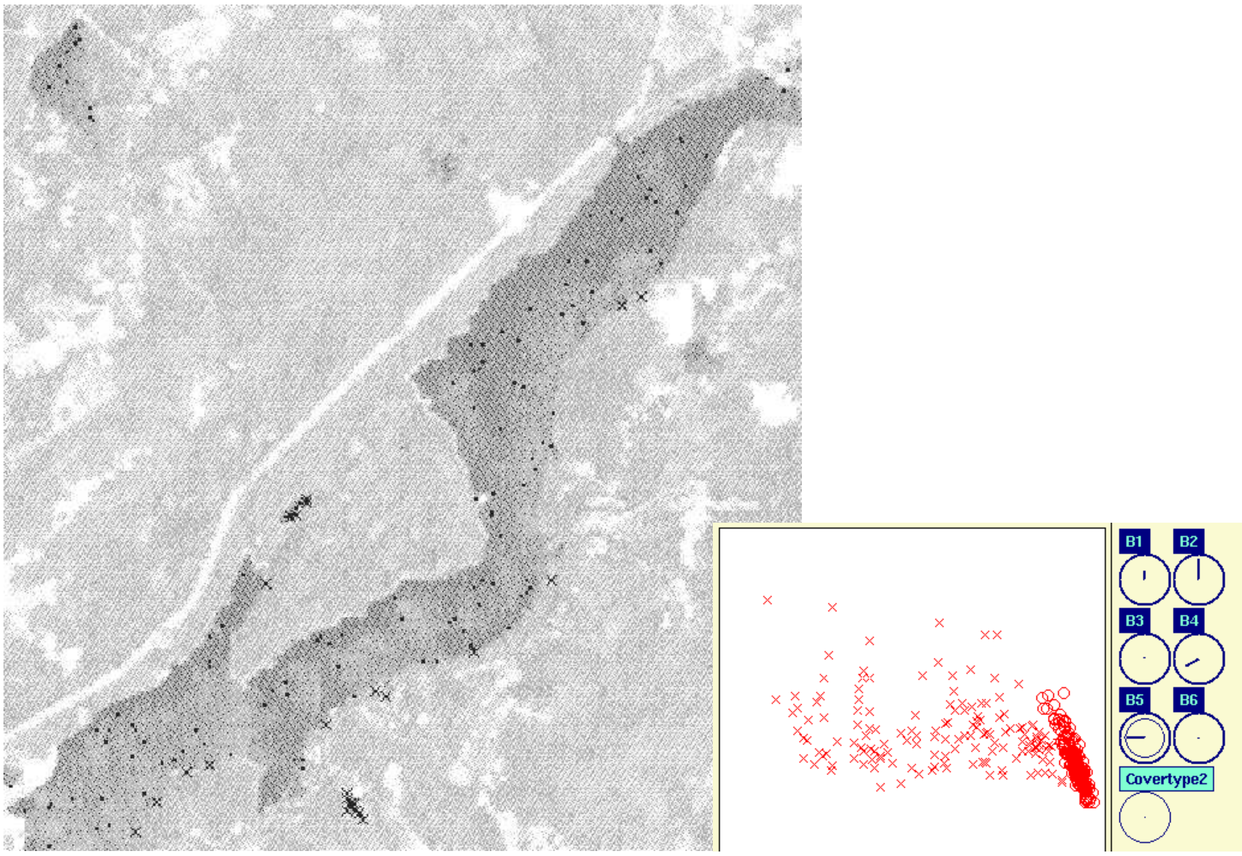

Figure 2: *The ArcView map view (left) shows the spatial region while the XGobi view (right) shows an interesting projection that permits to distinguish between two types of water. The cluster of points (marked with circles) detected in XGobi relates to the middle of the river and the small lake in the upper left corner of the ArcView map view. The remaining points (marked with* $\times$*'s) that are widely spread in the XGobi view fall onto the smaller ponds and the southern border of the river. The XGobi variable panel indicates that bands 2, 4, and 5 are major contributors to this projection.*

While we only consider main classifications such as water and vegetation in Example 1, this example demonstrates that water is not always equal to water and a quarry can be separated from areas that look similarly in the visible satellite image. This time we have measurements from 6 spectral bands recorded by the Thematic Mapper (TM) instrument of the Landsat earth observation satellite. The area under consideration relates to the border region between the states Vermont and New Hampshire. In Figures 2 and 3 we look at two very small segments of this area. The ArcView view in each of the two figures is based

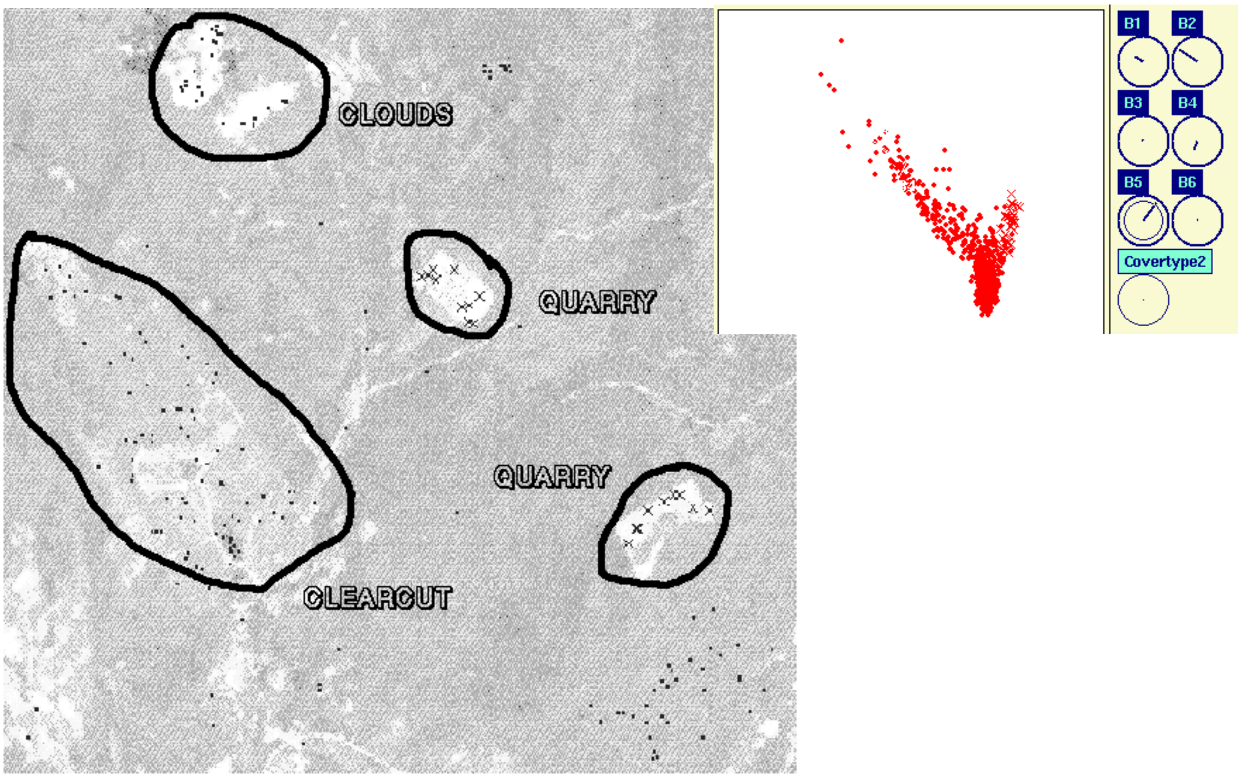

Figure 3: *The ArcView map view (left) shows the spatial region while the XGobi view (right) shows an interesting projection that permits to distinguish among quarry regions (marked with ×'s), a clearcut area, and clouds. The XGobi variable panel indicates that bands 2 and 5 are major contributors to this projection.*

on bands 4, 3, and 2, only. For the XGobi views, we took random samples of points from known origin. The ArcView images have been processed with an image processing program after the analysis to yield a better gray scale representation. On a computer screen you would see red symbols on a mostly green/blue background.

In Figure 2 samples of pixels from the water bodies have been taken. The big water mass that stretches diagonally across the ArcView view (left) relates to the Connecticut river. Three smaller water bodies are also visible. In the XGobi view (right) we see a concentration of circles that are clustered along a line and a large number of ×'s that are scattered in the plot. In the map view we see that the circles fall onto the middle of the river and the small lake in the upper left corner. These points may relate to factors such as a strong current, deep water, and no overgrown vegetation. Otherwise, the ×'s fall onto two smaller ponds and the southern border of the river. These points may relate to shallow water with algae or waterplants in the ponds or overgrown vegetation at the edge of the river. Note that there are no ×'s at the northern border of the river — an indicator that there is no vegetation on this border. Most importantly, the visible ArcView view based on bands 4, 3, and 2 does not allow a distinction among different water bodies. However, the XGobi projection allows such a distinction since, as the XGobi variable panel indicates, band 5 which is not used in ArcView (in addition to bands 2 and 4) is a major contributor to this projection.

In Figure 3 the ArcView view (left) shows a region where 2 clouds, a clearcut area, and two quarry regions have been classified as ground truth. In the XGobi view (right) we can distinguish three regions of points. We brushed the points from the quarry regions with an × in the ArcView view and notice that all these points fall into one of the three regions. However, there are additional points in this region that have not been marked. This might be an indicator for an addional quarry region that has been differently classified in the ground truth. Through brushing in XGobi we would also see where these points are located on the map. Note that once again bands 5 and 2 are major contributors to the XGobi view but band 5 is not a part of the ArcView view.

EXAMPLE 3: AGRICULTURAL SCENE FROM THE IMPERIAL VALLEY

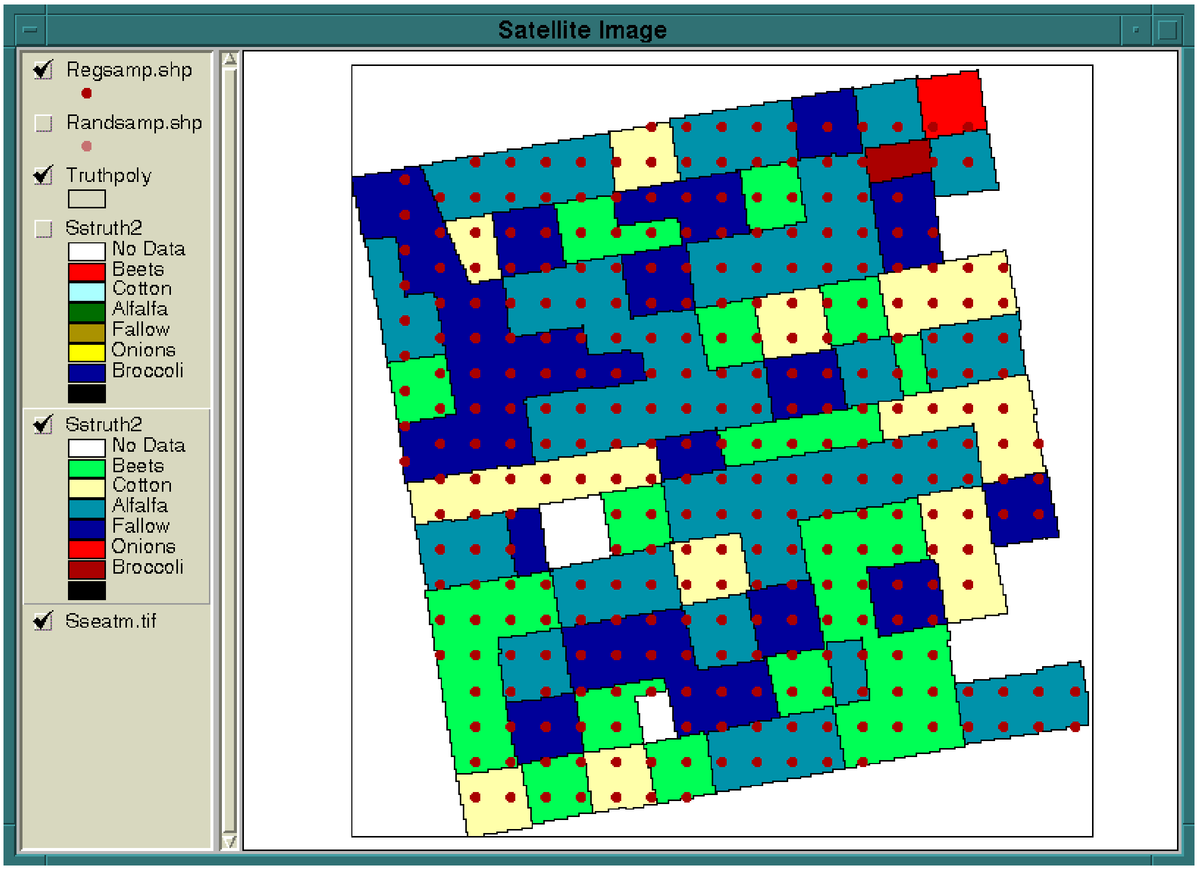

Figure 4: *The ArcView map view shows the reported crop information for an agricultural scene and the sampling locations which have been used for further analysis in XGobi and XploRe. Six crops are identified from the ground. For fields with no crops or mixtures of crops no information has been recorded. There are 7 bands of remotely sensed information available for clustering and comparison with the ground truth.*

In this example we are looking at data from 7 bands recorded by a Landsat–4 TM instrument on December 12, 1982. The scene under consideration represents a very small area of the Imperial Valley in California. In fact, we only consider 124 fields with known crop information provided by the Imperial Valley Irrigation Board. See [11] and [12] for additional details on the data and assessments of different classification techniques. Figure 4 shows the known crop types for the area under investigation. It is a reproduction within ArcView that is based on Figure 2 in [12]. We took a systematic random sample of 314 locations for further analysis in XGobi and XploRe.

As usual, we make use of XGobi's grand tour feature to detect clusters. Figure 5 shows such a cluster in the XGobi view (right). The points that have been brushed (with an open box) fall all into fields of beets in the ArcView map view (left). The ArcView map suggests that some points in the beets fields have been missed through the XGobi classification. This is not the case. As Figures 3, 4, and 5 in [12] indicate, there seem to be streets bordering each field. The points that appear to be located within fields of beets according to the inprecise ground truth used in ArcView most likely fall onto streets, thus yielding quite different wavelength measurements (and therefore projections in the XGobi view) than points from the fields of beets.

Before the next step we deleted points from XGobi and ArcView that have been classified as beets in the previous step, thus we are conducting a hierarchical analysis in this example. Figure 6 shows another cluster (brushed with an open box) in the XGobi view (right) that relates to fields of alfalfa in the ArcView map view (left). However, a large number of alfalfa points in the map is not highlighted. [12], again, provides an explanation: There are "new" and "old" alfalfa fields. Unfortunately, this additional information was not

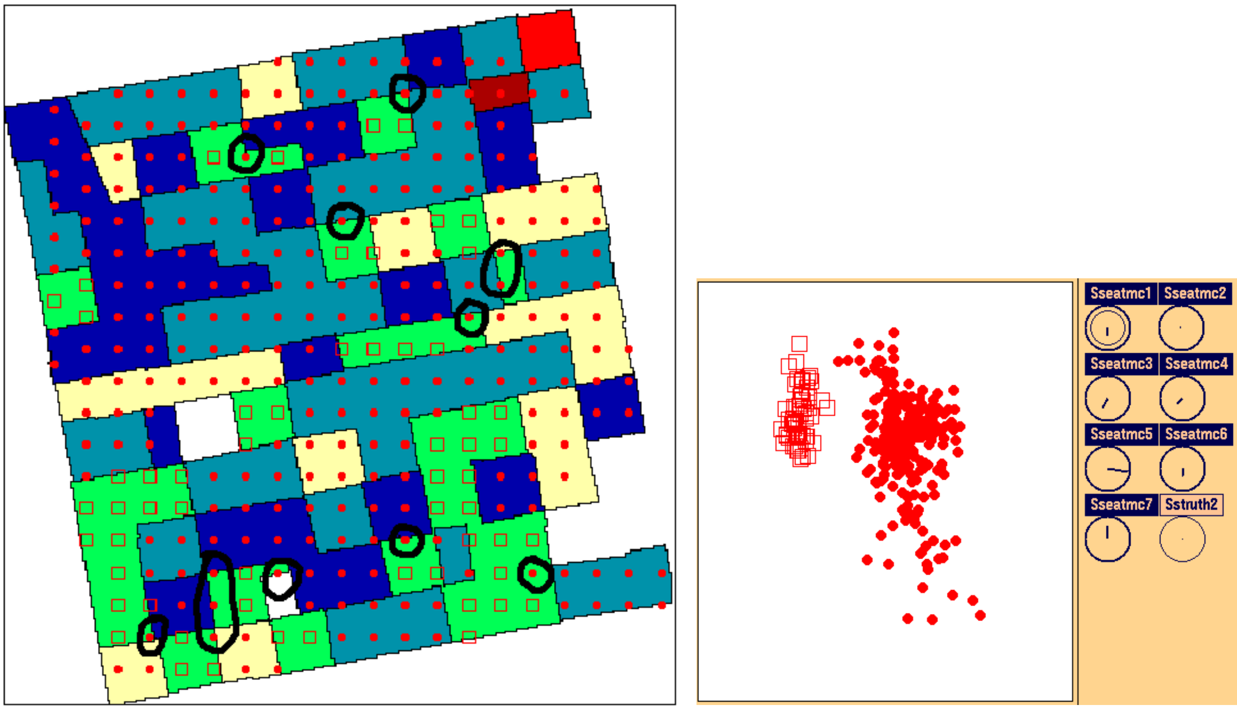

Figure 5: *The ArcView map view (left) shows the spatial region while the XGobi view (right) shows an interesting projection that permits to distinguish between beets (open boxes) and other crops (filled circles). Points that appear to fall on beets fields but are not contained in the XGobi cluster have been circled in the ArcView map view. From additional sources we know that these points most likely fall onto streets dividing or surrounding the fields.*

available for our analysis. However, it seems to be very likely that our given projection in XGobi allows a distinction between "new" and "old" alfalfa fields.

One should note that in Figure 6 we also brushed the single sampling point that falls into the broccoli field. In the XGobi view the corresponding filled box appears at one edge of the alfalfa cluster. It would be interesting to have a larger sample of points from the broccoli field and see if a distinction between alfalfa and broccoli is possible.

In our interactive environment we would try to find additional clusters in XGobi that allow to distinguish among the other type of alfalfa, cotton fields, and fallow fields. Since we have only two sample points for onions, it is very likely that these will not be identified as an additional crop. Taking more sample points from this crop's field would probably help in clustering it.

If we look at the XGobi variable panels in Figures 5 and 6, we see that each of the 7 bands has a non–neglectable influence on at least one of the visible projections. Any classification approach that tries to eliminate any of the bands will most likely produce a less precise classification.

In addition to the visual approach in XGobi presented so far we make also use of XploRe's clustering capabilities to analyze this data set. XploRe supports two basic clustering methods, i. e., hierarchical clustering and partitioning clustering. Partitioning methods (`kmeans` in XploRe) require an initial partition. Other k–means clustering methods, like adaptive k–means clustering, are also available in XploRe.

In this example we make use of a hierarchical method. For this approach interpoint distances of cluster centers will be used to build additional clusters. We start with n clusters that contain one observation each and successively merge clusters together. XploRe allows different hierarchical methods like single linkage, complete linkage, average linkage, Centroid linkage, Ward method, and Lance– and Willams method. For a short overview of these methods see [16], for a more detailed overview see [20], and for an overview of methods implemented in XploRe see [13].

To use the hierarchical method we have to select a distance measure and one of the previously listed methods. We choose the Euclidean distance and the Ward method. The Ward method minimizes the

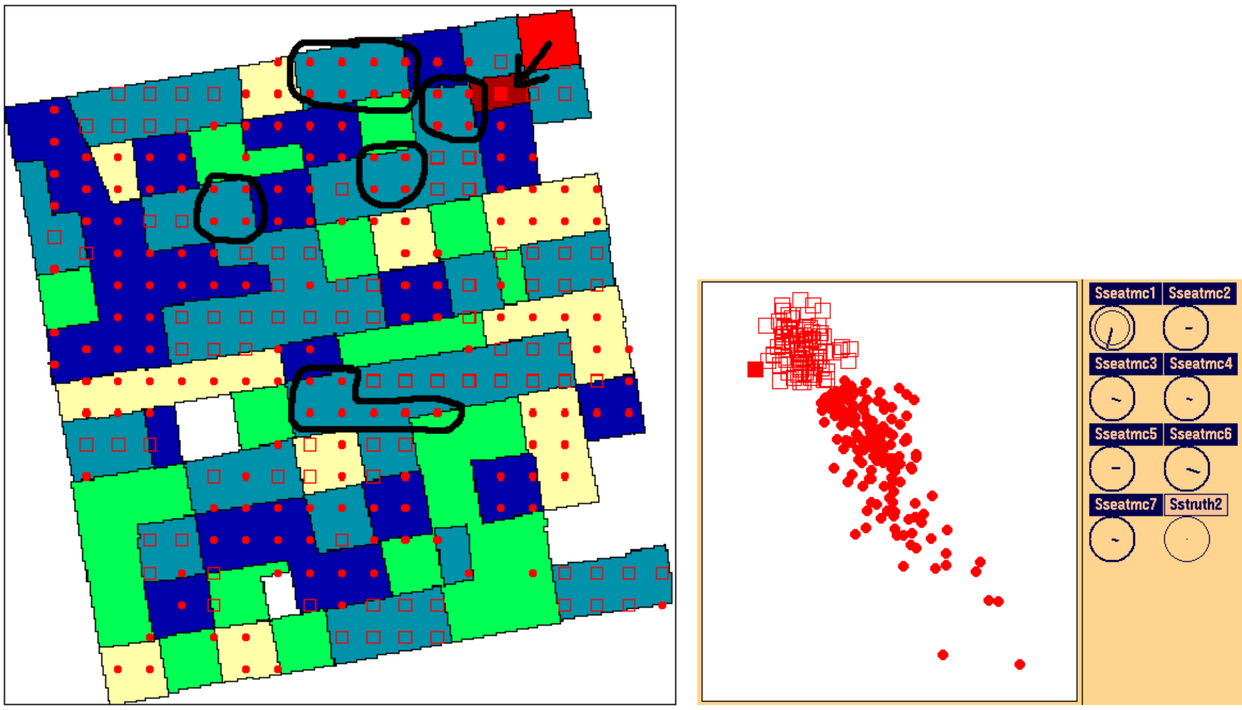

Figure 6: *The ArcView map view (left) shows the spatial region while the XGobi view (right) shows an interesting projection that permits to distinguish between alfalfa (open boxes) and other crops (filled circles). Alfalfa fields that are not contained in the XGobi cluster have been circled in the ArcView map view. There are "new" and "old" alfalfa fields. The cluster in XGobi most likely relates to only one of these types. Broccoli (just one sample point represented by the filled box) has values similar to alfalfa.*

"within" cluster variances. The dendrograms in Figure 7 show the logarithm of the sum of the "within" cluster variances on the y–axis. We see at which levels observations and clusters are merged together (bottom: all 313 observations[2], top: one cluster). Since the variances of the clusters vary, we applied clustering on the original data and on the standardized data. Both dendrograms show a large increase of the sum of the "within" cluster variances if we merge the last two clusters. The dendrogram of the standardized variables shows also an increase of the sum of the "within" cluster variances if we have four clusters.

Since we know the clustering based on ground truth, we can compare the results of the clustering algorithm (based on the original data) and the true groups as in Table 1. The Ward methods behave a little bit worse on the standardized data (not shown). However, Table 1 shows that with two clusters (left part) just group 1 (beets) is somewhat separated from the other crops. An increase to four clusters (right part) shows that group 3 (alfalfa) is split into three of the four clusters. This is not surprising since we already know that there are different types of alfalfa. Group 1 (beets) is separated very well from the other crops. The first cluster does not only contain parts of group 3 (alfalfa) but also groups 2 (cotton) and 4 (fallow). Obviously, much more than four clusters are required to distinguish among these crops. This matches the results of [11] where a clustering method based on unsupervised signatures resulted in 19 clusters. Since groups 5 (onions) and 6 (broccoli) contain only 2 and 1 observations, respectively, it is basically impossible to detect these as separate clusters.

Figure 8 shows some good bivariate projections based on the partition found in the data. The two cluster projection (left) shows a strong linearity within the data whereas the four cluster projection (right) shows how well the clusters are separated in the data.

[2]From the dataset one observation was deleted since the measurement of all channels was zero.

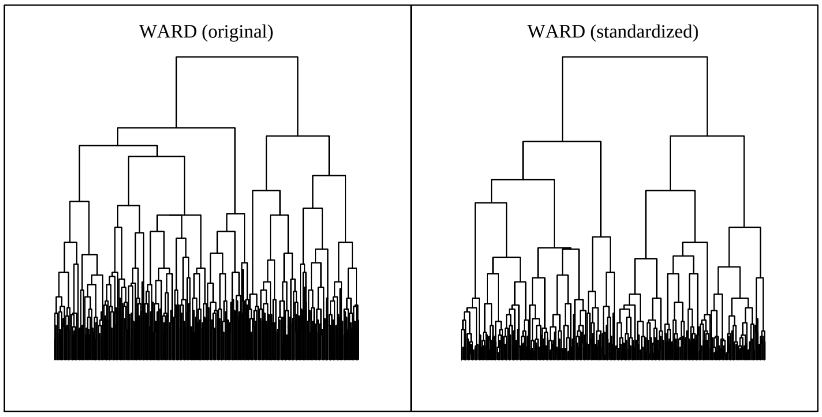

Figure 7: *The dendrograms for the original data (left) and standardized data (right) indicate how clusters are merged together. At the bottom we have all 313 observations and on top we have one cluster. On the y–axis we see the logarithm of the sum of the "within" cluster variances.*

Table 1: *Comparison of clustering (based on the original data) and the ground truth based on two clusters (left part) and four clusters (right part). The numbers 1 to 6 on top of the table stand for the 6 crops, i. e., beets, cotton, alfalfa, fallow, onions, and broccoli.*

```
[ 1,]
[ 2,]
[ 3,] Crosstable for variables 1, 2
[ 4,]
[ 5,]           |      1.0000  2.0000  3.0000  4.0000  5.0000  6.0000 |
[ 6,] ---------|-----------------------------------------------------|---------
[ 7,]  1.0000  |        9      47      70      72       2       0    |      200
[ 8,]  2.0000  |       58       0      52       2       0       1    |      113
[ 9,] ---------|-----------------------------------------------------|---------
[10,]           |       67      47     122      74       2       1    |      313
[11,]
[12,] Chi^2 test of independence
[13,]
[14,]   chi^2 statistic:                        141.45
[15,]   degrees of freedom:                          5
[16,]   significance level for rejection:   0.0000
[17,]
[18,]   contingency coefficient:               0.56
[19,]   corrected contingency coefficient:     0.79
```

```
[ 1,]
[ 2,]
[ 3,] Crosstable for variables 1, 2
[ 4,]
[ 5,]           |      1.0000  2.0000  3.0000  4.0000  5.0000  6.0000 |
[ 6,] ---------|-----------------------------------------------------|---------
[ 7,]  1.0000  |        4      45      35      71       2       0    |      157
[ 8,]  2.0000  |        5       2      35       1       0       0    |       43
[ 9,]  3.0000  |        1       0      51       0       0       0    |       52
[10,]  4.0000  |       57       0       1       2       0       1    |       61
[11,] ---------|-----------------------------------------------------|---------
[12,]           |       67      47     122      74       2       1    |      313
[13,]
[14,] Chi^2 test of independence
[15,]
[16,]   chi^2 statistic:                        392.40
[17,]   degrees of freedom:                         15
[18,]   significance level for rejection:   0.0000
[19,]
[20,]   contingency coefficient:               0.75
[21,]   corrected contingency coefficient:     0.86
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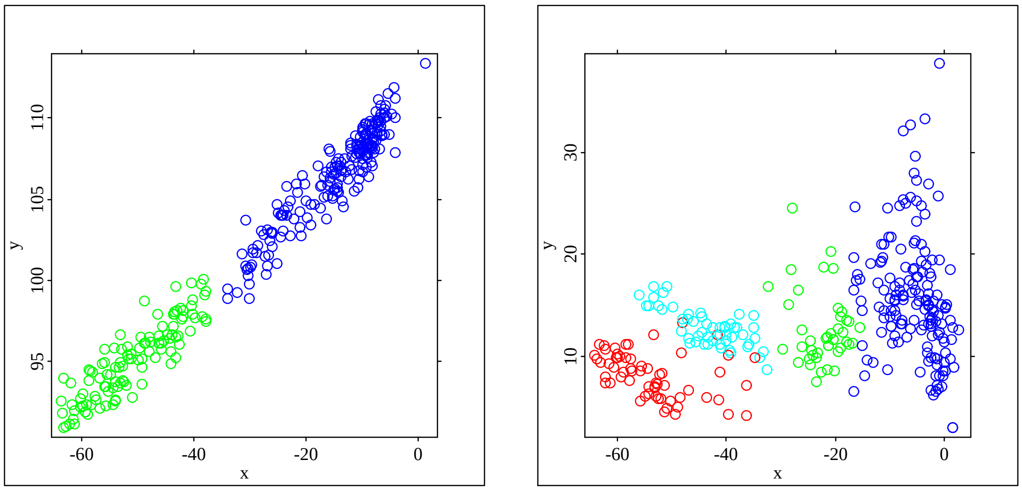

Figure 8: *Bivariate projections based on the partition found in the data. The two cluster projection (left) shows a strong linearity within the data whereas the four cluster projection (right) shows how well the clusters are separated in the data.*

SUMMARY AND FUTURE DIRECTIONS

In this paper we described the use of the ArcView/XGobi/XploRe software environment for the exploration and analysis of satellite images. Within this environment we are capable to detect interesting features of the remote sensing imagery due to its appearance in a series of dynamic plots in XGobi. We can also conduct an analytical statistical analysis of the data in XploRe.

Further work can be directed towards two directions. First, one should consider how existing classification techniques of remote sensing imagery can be combined with the visual approach highlighted in this paper. What is the gain if we combine these methods, how many additional percent of pixels do we classify correctly?

The work presented in this paper should not be misunderstood. We do not claim at all that the classification through dynamic statistical graphics presented here is better than any existing classification technique. But we are convinced that existing classification techniques combined with the graphical approach help to produce better classification results in an easy way. This should be further investigated.

Direction two deals with possibilities for improvements of the software environment. For example, it is absolutely necessary to solve one restriction of this environment, i. e., the fact that only one of the graphical links is fully functional at a time. For example, if we brush points in the XGobi view, they are also brushed either in ArcView or in XploRe — but not in both other programs at the same time what one would expect from such a linked environment. A solution has been designed (see the part on “hierarchical” linked brushing in [31] and [26]) but it has not been implemented yet.

There exist other possible extensions that would be particularly useful for the exploration of satellite images. As we have seen in all of our examples, we typically only use a very small subset of the pixels of a satellite image. So far, we used individually written AVENUE scripts in ArcView to do this sampling, e. g., systematic random sampling or stratified sampling based on ground truth such as water, road, or urban surfaces. An easily accessible collection of sampling mechanisms in this environment would be ideal.

Also the concepts of “geographic brushing” through ArcView (e. g., brush all points that are at most 1 km away from a known water source) and “statistical brushing” through XploRe (e. g., brush all points where the greenness index — a function based on measurements of some of the satellite bands — falls into a given range to show actively growing vegatation) would be additional useful extensions of this software environment for the exploration of satellite images and other geographically referenced data.

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