AVIRIS AND ARCHAEOLOGY IN SOUTHERN ARIZONA

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Introduction

Arizona is a state that is experiencing unprecedented growth in both its economy and its population. Cities like Phoenix and Tucson are expanding at exponential rates, converting open space to tract home communities and strip malls. Underneath both Phoenix and Tucson, and extending out far into the Sonoran Desert, are tens of thousands of archaeological sites associated with the prehistoric culture known as the Hohokam (Crown and Judge, 1991; Gumerman, 1991). While archaeologists do not like the fact that dozens of Hohokam sites are destroyed every day in the name of progress, we do take some small comfort in the federal legislation that mandates that we get to find, document, excavate, and report on those sites—thereby preserving some of Arizona's rich cultural heritage—before they are destroyed. The most expensive and time-consuming aspect of this work, known as Cultural Resource Management (CRM), is survey.

Most projects involve surveying a large piece of land on foot. Sites are recorded and ranked by perceived importance. The most important of these sites are either excavated (last resort) or avoided entirely (preferable), depending on the flexibility of the developer. If archaeological sites in southern Arizona were easily seen on the surface, as they generally are in other parts of the Southwest, survey would be relatively straightforward and inexpensive. However, Hohokam sites exhibit little to no surface expression that we can detect with the naked eye. The results of this dilemma have been disastrous. Construction crews find or destroy sites archaeologists missed and archaeologists sometimes end up digging in locations that yield no information.

The main contributing factors to the relative invisibility are dense vegetation cover and what archaeologists refer to as *site formation processes* (Schiffer, 1987). The Sonoran Desert, due to its complex geology and bimodal rainfall pattern, allows for a great degree of biotic diversity. The landscape is literally blanketed with vegetation ranging from sage brush to saguaro cacti to mesquite, greatly reducing site visibility from the ground or the air (Figure 1). Site formation processes, which are natural and cultural processes that affect an archaeological site once it has been abandoned by its prehistoric occupants, are perhaps the most devastating with respect to site visibility. The effects of natural processes such as erosion, weathering, sedimentation, and Aeolian deposition on an archaeological site over hundreds of years produce a fairly uniform result throughout the Sonoran Desert region: Sites are almost entirely invisible from the surface. Over time, sediments fill in all but the most prominent and large archaeological features until the ground surface appears completely flat (Figure 2). It is actually quite easy to walk over an entire Hohokam village and not know it is there, 30 cm beneath the surface (Figure 3).

Figure 1. Typical vegetation cover in the Sonoran Desert that results in low site visibility.

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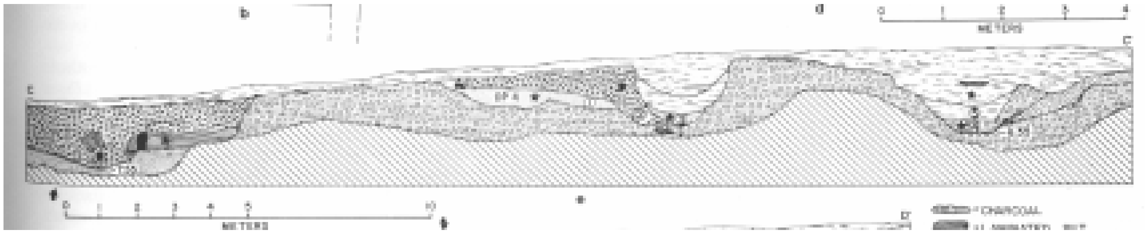

Figure 2. Typical stratigraphic profile from a Hohokam site. Archaeological features like canals (right of center) are often filled in with sediments until they are completely level with the modern ground surface, rendering them invisible to the naked eye and, potentially, remote sensing systems. (Haury, 1976)

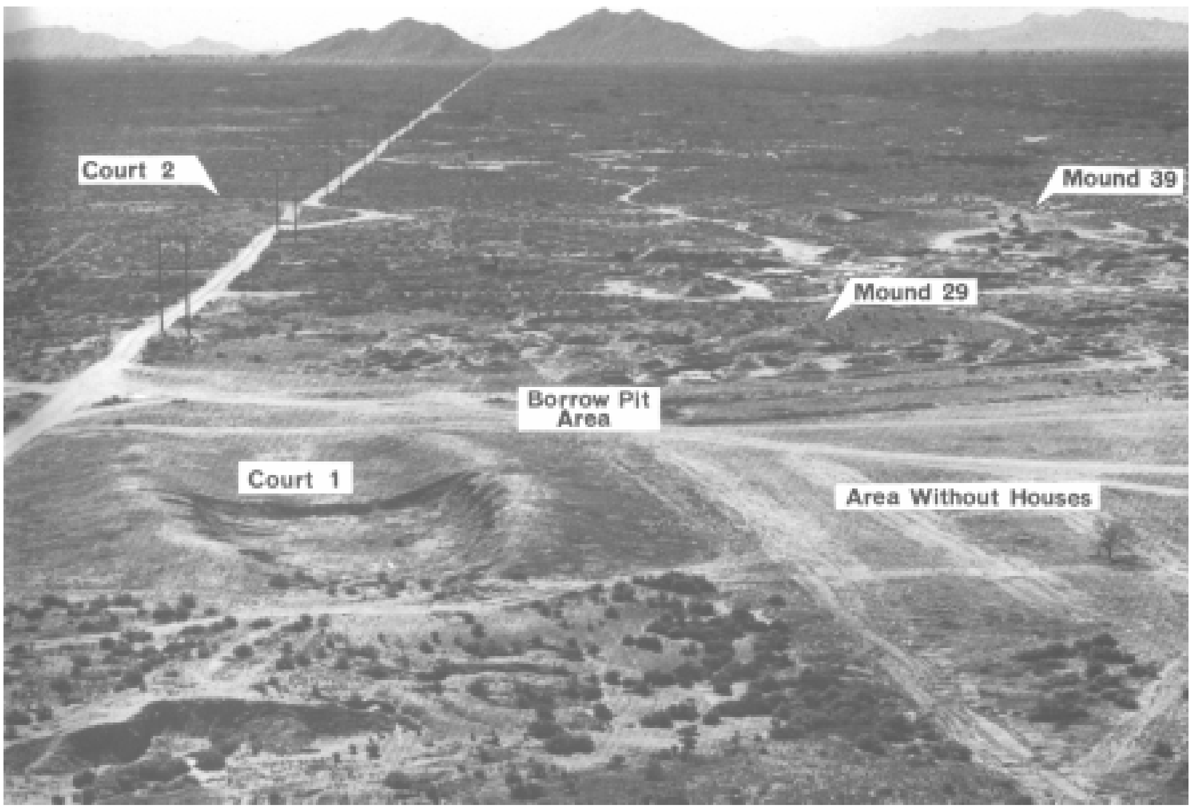

Figure 3. The Pre-Classic Hohokam site Snaketown, before excavation. Surface expression of archaeological features is minimal, even at a site as large and as important as this one. (Gladwin et al, 1938)

Spectral remote sensing holds a great deal of potential for archaeologists, especially now that advances in technology have moved spatial and spectral resolution into the range that is useful to us. The reasons that archaeologists working in southern Arizona have not embraced airborne and satellite remote sensing so far are that (1) the high spatial resolution systems (IKONOS) only cover the visible and near-Infrared portion of the spectrum, one in which sites are invisible, and (2) systems that cover more portions of the spectrum (Landsat) tend to do so only broadly and have large pixels (30 m or greater). While using thermal Infrared remains a possibility, it is still worthwhile to explore the utility of remote sensing that takes advantage of high spectral resolution, for it has not been tried before.

It is my belief that certain types of archaeological sites in southern Arizona may contain within them mixtures of materials that when seen as whole by a hyperspectral remote sensing system could be differentiated from surrounding soils and rocks using a wide array of image processing techniques including the standardized "hourglass processing" regime available in ENVI. This study uses hyperspectral remote sensing data for southern Arizona obtained by AVIRIS, combined with ancillary data from the USGS and the Arizona State Historic Preservation Office (SHPO), in an effort to find a solution to the problem of site invisibility. After a thorough discussion of the methods used in analysis, the results of this study are presented. These results, as the reader will soon see, are indeed promising, but I must caution that they are only preliminary. Much additional research, including fieldwork, is required in order to validate the findings of this study and prove the utility of hyperspectral remote sensing for archaeological site detection in southern Arizona.

Methods

The first step in my analysis was finding the appropriate AVIRIS data. Candidate data sets had to (1) cover some part of southern Arizona, (2) contain within them areas that were not impacted by urban sprawl, and (3) contain within them regions where archaeological sites were known to exist. The coordinates for each candidate data set were plotted on a map and checked against known archaeological site locations, which was done via additional maps and personal communication with other archaeologists who work in the region. Out of the archived data sets examined, only one met all of the established criteria.

Each of the nine AVIRIS radiance-calibrated scenes were subjected to atmospheric correction and conversion to apparent reflectance using HATCH (Figure 4), a program still currently under development within the Center for the Study of Earth from Space (CSES) at the University of Colorado, Boulder. Several parameters within the HATCH input file had to be modified in order to ensure an accurate correction and conversion. Date, time of day, surface elevation, location (lat/long), visibility, and aircraft altitude all had to be changed to match local conditions at the time the data were acquired. HATCH was directed to use the Full Width Half Maximum (FWHM) file that accompanied the data and to weight the seventh water vapor band (0.86, 1.25). The Z-profile of each scene was examined and any bands that exhibited a high degree of noise, were overlapping, demonstrated severe over-correction by HATCH, or did not contain data were thrown out. Out of the 224 bands on the AVIRIS system, 58 bands (1-7, 32-35, 96, 105-117, 151-172, 213-224) were removed due to one or more of these problems. The remaining 166 bands were used extensively throughout the rest of this study.

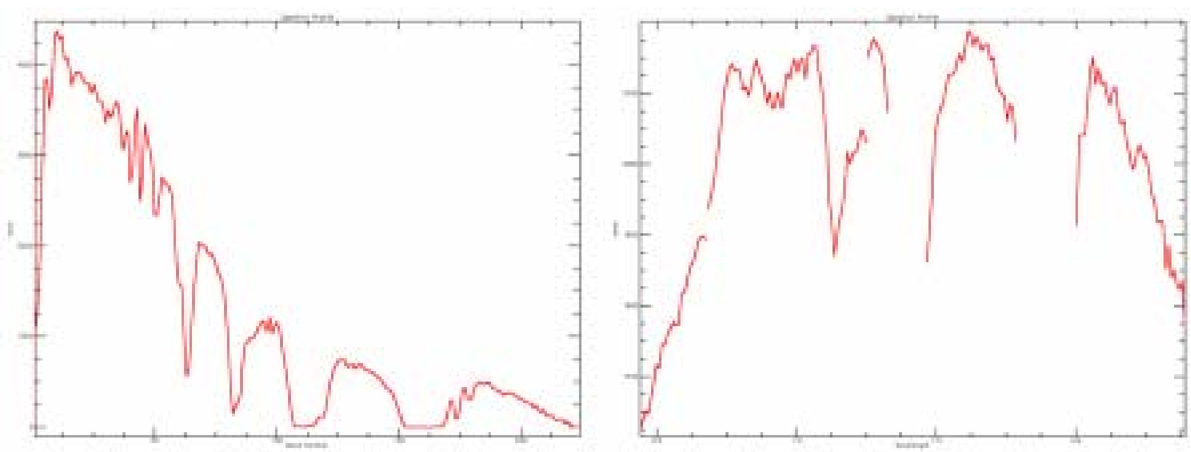

Figure 4. Example of atmospheric correction and conversion of radiance (left) to apparent reflectance (right) using HATCH.

The next step in my analysis was to obtain relevant ancillary data. 1:100,000 scale digital line graphs in Option Format were downloaded from the USGS WebGLIS server to aid in registering the AVIRIS scenes to a UTM map projection. Digital elevation models (DEMs)—accurate to within 30 meters—were downloaded to aid in data interpretation and presentation, as well as to increase the accuracy of the atmospheric correction carried out by HATCH. By far the most important ancillary data set needed for this study was a relational database that contained accurate locations for and information about known archaeological sites in the region. The State Historic Preservation Office for Arizona, in cooperation with Arizona State University and the University of Arizona, maintain just this kind of database (AZSITE). While AZSITE mainly functions as an archive to be used by Cultural

Resource Management firms and other government agencies, it can also be accessed by individual researchers who have the proper clearance. Getting access to this sensitive data was not easy and required the acceptance of a non-disclosure agreement with respect to accurate site locations if I ever decided to present the findings of this study in a public forum. In accordance with this agreement, I have gone to great lengths in this paper to avoid making any sort of reference to exactly where in southern Arizona these data derive from. However, all delineated sites presented in the images below are exactly where they should be, even though geographical references and scales are not present.

Once clearance to AZSITE was granted, I instructed the database administrator to search the extent of my entire AVIRIS flight line for known archaeological sites. When the total number began to exceed 3000, we both thought it wise to limit the search to the types of sites that would be of particular interest to me. A new search was conducted that only looked for sites that were prehistoric (before Spanish contact, containing no modern man-made materials) and exhibited some form of surface expression. I knew that sites with surface expression were rare (hence the need for this study), but if any existed within the study area I might be able to increase the success of my analyses due to the fact that reflected light only penetrates the upper few microns of the earth's surface. Buried archaeological sites would not do me much good. A list of candidate sites was compiled and the database administrator generated a geo-referenced ArcView shape file (UTM projection) that contained both their locations and site type. The importance of this shape file for my study cannot be overstated. Once the AVIRIS scenes were warped to a UTM map projection, this file could be accurately overlaid on each scene, thereby providing exact site locations within an image and allowing for comparison between known sites and predicted sites.

I next selected three adjoining scenes that covered an area of interest (Figure 5). This area was chosen for its "pristine" condition—where native vegetation and archaeological sites are still relatively intact. I took each scene (unwarped) and performed several standard "hourglass processing" analyses in ENVI (MNF, PPI, n-DV, Identification, MTMF, Mapping location and abundance) focusing on different parts of the spectrum (especially NIR and the 2-2.5 µm region). My thought was that archaeological sites might show up as an endmember in portions of the spectrum not detectable to the human eye, where differences in vegetation and soil composition show up more clearly. These initial analyses were focused on deriving archaeological site locations from the data themselves. Candidate Regions of Interest (ROIs) were made into masks, and the resulting images were warped to a UTM map projection using 20-30 Ground Control Points (GCPs). The warped masks were thresholded back into ROIs, now geo-referenced. The AZSITE shape file was overlaid on a warped version of each scene and the locations of the ROIs were compared to known site locations.

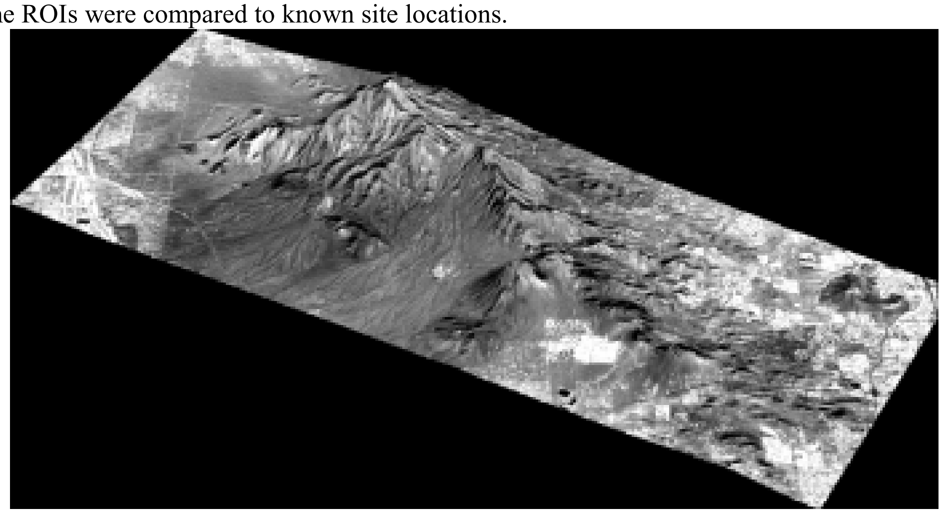

Figure 5. The three adjoining AVIRIS scenes draped on a DEM.

Unfortunately, standard hourglass processing techniques produced negative results. If archaeological sites are indeed endmembers, they are very subtle ones that are most likely overshadowed by endmembers associated with vegetation and mineralogy. Even setting the PPI iterations to maximum (32,767) failed to yield any pure pixels that matched with known site locations. Part of the problem extends from the fact that by focusing on only small portions of the spectrum the resulting data dimensionality is low (7-10 endmembers). In a last ditch effort to stick to standard processing techniques, I tried Maximum Noise Fraction (MNF) color composites and ratio images, as well as Spectral Angle Mapper (SAM) supervised classification (based on average spectra derived from sites within the park). Both of these methods produced disastrous results. Known archaeological sites were still invisible in the

MNF images and the SAM, set to a very narrow threshold, still classified the bulk of each image as an archaeological site.

I was initially very disheartened by the results of standard hyperspectral image processing. Instead of giving up, I decided to try something a little unusual. It is clear that archaeological sites are mixtures of several different materials, affected by the elements over hundreds of years, and hence they would never show up as pure pixels in a PPI image. But what if archaeological sites are *predictable mixtures*? That is, perhaps the mixtures of materials that compose sites are fairly constant in this region. As such, they could be classified as an coherent endmember, albeit one that hourglass processing would never find on its own. If average spectral profiles from known archaeological sites in the region were fed into a Mixture Tuned Matched Filter (MTMF), if it was given some direction, ENVI might be able to find archaeological sites because it would know what to look for.

In order to test the hypothesis that a directed MTMF should find archaeological sites, I chose one scene out of the three selected that I knew contained many archaeological sites of different types. The scene contains a mixture of urban sprawl and protected open space. As such, there are sites in the AZSITE database that still existed on the surface as well as some that were destroyed shortly after they were recorded and mapped. I also decided to increase the spectral range of the MNF rotation to include the entire spectrum. Since the "archaeological endmember," if it exists, is subtle, having more dimensions to work with will allow for a more accurate representation of that endmember. The MNF rotation produced 30 endmembers, which is not too surprising considering the mixture of man-made and natural materials in the scene.

The MNF image was then polynomially warped with Nearest Neighbor interpolation to a UTM projection using 20 GCPs. The AZSITE shape file was then placed on top of the image. The same shape file was opened in ArcView and the region covered by the scene was analyzed to glean site types for each delineated site. Ultimately, I focused on two site types for my analysis: pithouses and mounds. Each has surface expression and each would contain a human-induced mixture of various materials ranging from sediments to organics. I located three intact pithouses in the warped MNF image and turned each one into a member of a Region of Interest (Figure 6). A mean MNF spectra was then derived for this ROI. The same procedure was carried out for mounds, of which there was only one in the image, unfortunately. These two mean spectra (Figure 7), which I believed represented two distinct archaeological endmembers, were then fed into a MTMF analysis of the unwarped MNF image. The pixels that had the highest MF score and the lowest infeasibility for each site type were selected and turned into members of an ROI. Both ROIs were then converted to masks that were subsequently warped using the same methods applied to the MNF image. Each warped mask was then thresholded back to an ROI and overlaid on the warped MNF image, upon which was also overlaid the AZSITE shape file containing known sites for the area. MTMF-predicted site locations for each site type (pithouses and mounds) were then compared to the locations of the known sites (see Figure 8). The results of this analysis were both surprising and encouraging.

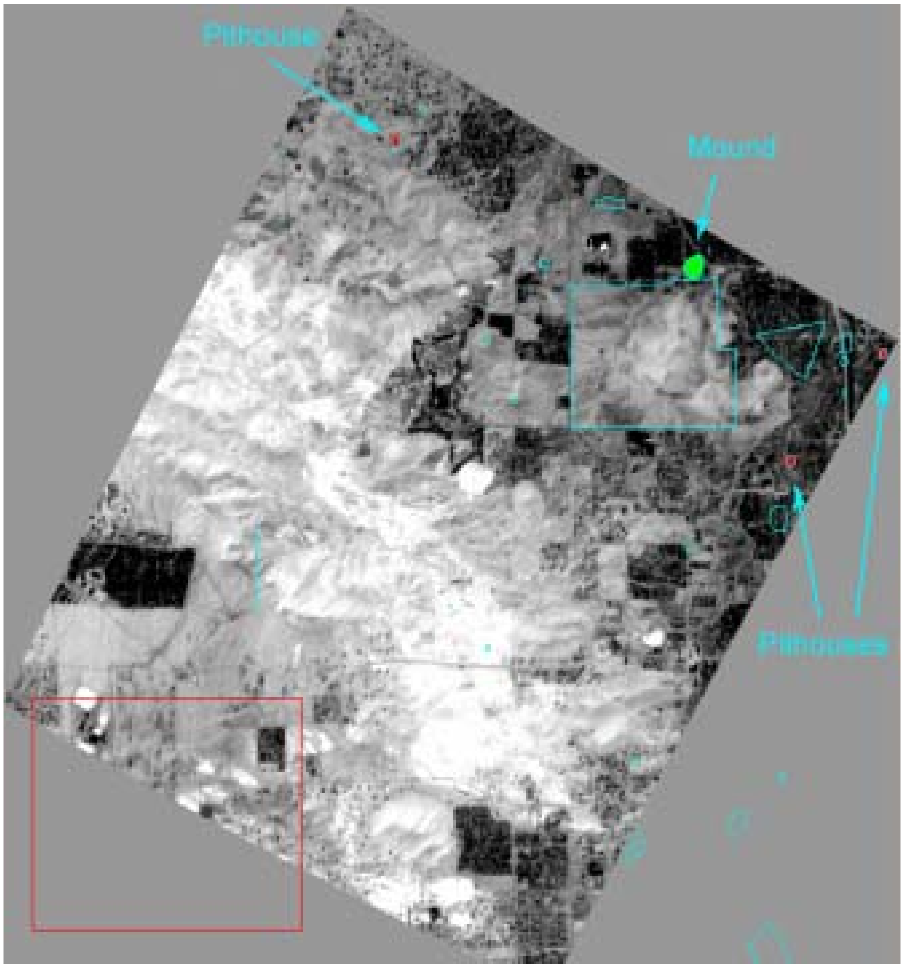

Figure 6. Warped MNF image with known sites delineated (teal). Red represents the ROI created for pithouses, Green the ROI created for mounds.

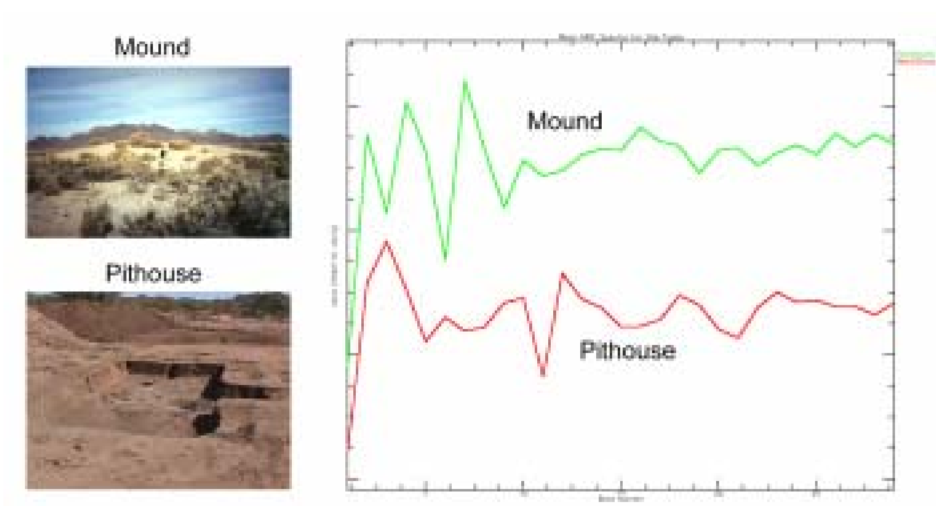

Figure 7. Examples of the two site types used in this study and their average MNF spectra as derived from the AVIRIS scene.

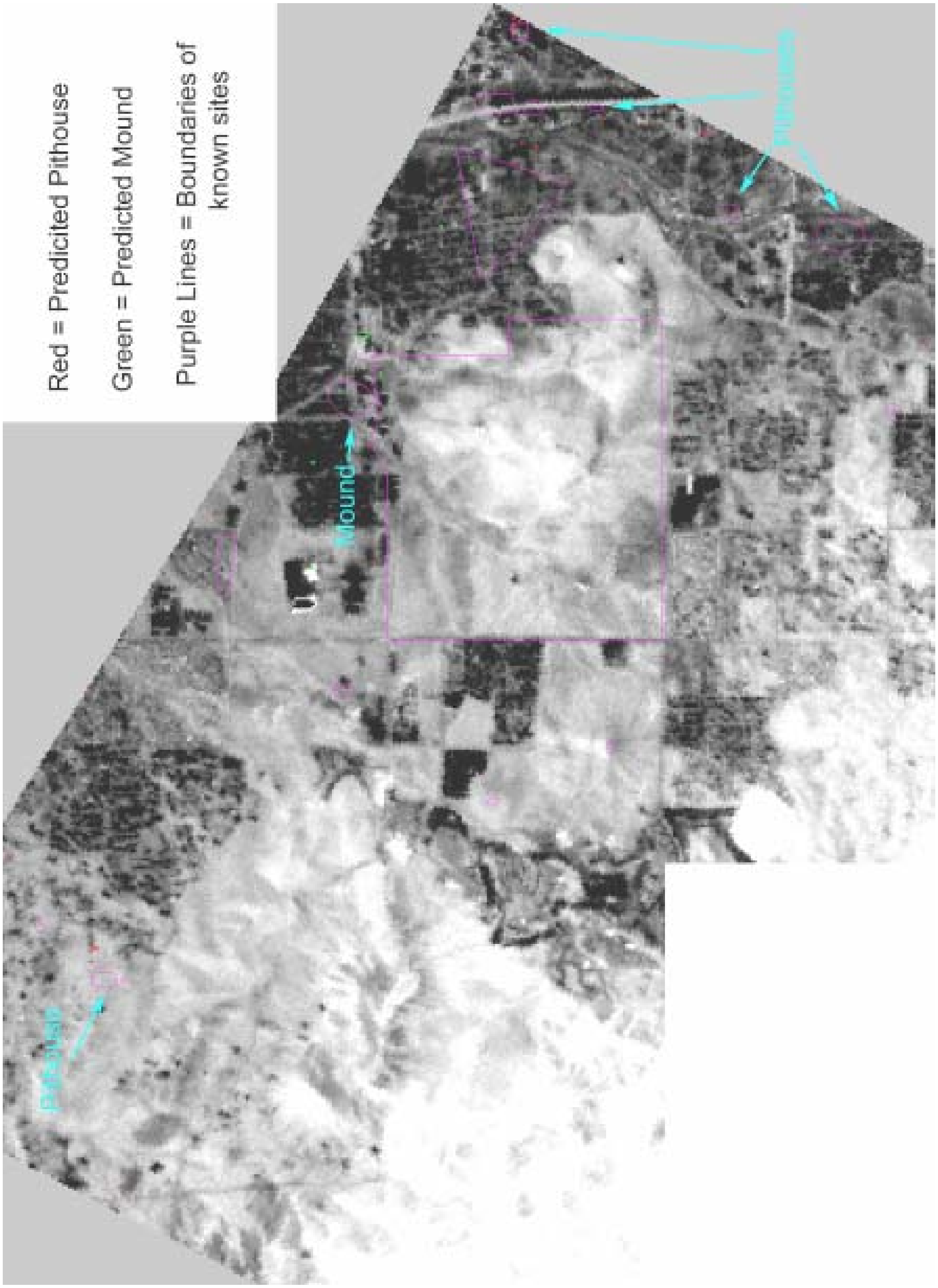

Figure 8. MTMF-predicted site locations (Red for pithouses, Green for mounds) compared to known site locations (Purple).

Results

The success of the directed Mixture Tuned Matched Filter analysis varied between the two site types. I was able to relocate all three pithouses used to create the average MNF spectrum for that site type (see Figure 8). Accuracy ranged from dead-on (center of bounded area in the AZSITE file) to within 70 meters. The MTMF also classified a handful of smaller rockpile sites as pithouses and pointed out a few additional locations for sites that are not included in the AZSITE file. This suggests that (1) perhaps the mixture of materials I attributed solely to pithouses might encompass a broader range of archaeological site types and (2) all of the archaeological sites contained within the scene are either not recorded in the AZSITE database or were missed in my search of the AZSITE database for sites that exhibited some form of surface expression. The MTMF missed the mound by approximately 140 meters. What is interesting to note, however, is that the AZSITE location for the mound contains within it three different modern roads. This suggests that the mound was either bulldozed to make way for the roads or the mapped location of the mound is inaccurate. If the mound was indeed bulldozed, the green pixels produced by the MTMF that show up near the mound might represent material from that mound that was relocated prior to road construction. If the mound itself is inaccurately mapped, the green pixels might represent the true mound. Ground truthing would greatly aid in clearing up this inconsistency. The green pixels that occur far away from the mound demonstrate one big problem with trying to locate mounds using an MTMF: Mounds are essentially large "bumps" composed of the surrounding soil. It is logical that other locations that are not mounds would look very similar, if not identical, to mounds if their soil composition was similar. These "stray" green pixels, though, occur very close to predicted pithouse sites or within other known sites. As with pithouses, perhaps the average MNF spectra for mounds encompasses more than just this one type of archaeological site.

One apparent problem with the MTMF analysis of this scene is the lack of predicted sites within the large semi-rectangular bounded area (Figure 8). While one green and one red pixel appear within the boundaries, the vast majority of it shows up site-free. At first this puzzled me greatly, since I knew that the area was full of sites. What is interesting is that the preserve contains sites that are fundamentally different (no pithouses) and much older than the ones I am looking for. A cultural tradition known as "Trincheras" built terraces and houses on the hill slopes contained within this area long before the Hohokam ever showed up in the region (Cordell, 1997). The Hohokam did not build their houses or mounds on slopes; instead they preferred flat areas (Haury, 1976; Crown and Judge, 1991; Gumerman, 1991). This type of cultural behavior could help explain why all of the MTMF-predicted pithouses and mounds occur only in the flat areas surrounding the hill, not on the hill itself. If predicted sites did show up on hill slopes, then I would have to completely rethink my methods. The fact the *none* showed up on hill slopes is indeed encouraging. If the AZSITE database was more accurate and delineated specific sites within the area, I might be able to create average MNF spectra for Trincheras sites—ones that are perhaps different than those associated with Hohokam sites—and look for more of them in the AVIRIS scenes.

An additional factor that may play a role in the apparent accuracy of this study is the amount of error introduced during the analysis phase. While great care was taken to use a large number of GCPs and to keep the RMS well below 0.500 when warping the AVIRIS scenes, MNF images, and masks, the warps were not perfect. It is quite possible that all of the warps are "off" by a few pixels. While nearest neighbor interpolation was used to preserve as much radiometric accuracy as possible, the technique is not perfect and some slight error was most likely introduced. On top of error introduced by the analyses I undertook, it is also quite possible that site locations recorded in AZSITE are not entirely accurate due to errors in field recording or data entry. Having said all of this, however, the results of the analysis presented here are still encouraging and further research is warranted to see if accuracy can be improved and if the techniques can be applied on a much broader scale than one AVIRIS scene.

Conclusions and Directions for Future Research

The initial results obtained using standard hyperspectral image processing techniques were not good. I believed that archaeological sites exhibited enough individuality as a coherent endmember that a Pixel Purity Index would detect them with no outside assistance. I was wrong. No matter what portion of the spectrum I focused on, no matter how high I set the iteration number, ENVI could not find the archaeological sites in my flight line on its own. Instead of throwing in the towel, I decided to rethink my methodology. If archaeological sites are indeed endmembers, they must be very subtle ones for ENVI to miss them. I went to known sites of different types and derived their average MNF spectra—now ENVI knew what to look for. A Mixture Tuned Matched Filter analysis focused on these average spectra produced some interesting results. While the accuracy could still be greatly improved through a further refining of techniques, the MTMF did a reasonable job of finding known sites once it was given some direction.

In what ways could the detection of archaeological sites using hyperspectral imagery be improved? What directions should future research take? There are two potential directions at the moment, both of which require fieldwork. The first would be to ground truth both the known site locations in the AVIRIS scene as well as the predicted ones from the MTMF analysis. This would very quickly establish which analytical steps, if any, introduced the most error. If the known sites are exactly where AZSITE says they are, then the image processing methods need to be refined. If the sites are where the MTMF analysis predicts them to be, including the additional ones not included in the database, then the techniques used here would be validated. The second would be to compile a spectral library for archaeological materials and site types in this region using lab and field spectrometers. This library could then be fed into an MTMF analysis or used in conjunction with continuum removal and Tetracorder to classify AVIRIS scenes within the flight line. The results of these analyses would hopefully be much more accurate than those presented above since ENVI would have examples of "pure" archaeological materials to work with.

On the whole, I believe that hyperspectral remote sensing holds great potential for archaeological site detection in southern Arizona. This study is the first of what I hope will be many more sophisticated uses of spectral remote sensing data in archaeology. If the techniques outlined above can be refined and their usefulness proven at larger and larger scales and across multiple AVIRIS flight lines, it could revolutionize how archaeologists conduct business in this part of the world once the technology becomes more widely available, affordable, and understood.

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