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Fusion of Information from Optical, Thermal, Multispectral Imagery and Geologic/Topographic Products to Detect Underground Detonations

Carroll Lucas

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5301 Shawnee Road
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6 March 1990

Phase I SBIR Final Report

(Classified Annex Published Separately)

Prepared for:

U.S. Army Missile Command
AMSMI-PC-BFA/DARPA Project Office
Redstone Arsenal, AL 35898

Defense Advanced Research Projects Agency
Building 7770, Room 107/Charles Piner
AMSMI-RD-DP-TT
Redstone Arsenal, AL 35898

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As the nuclear family of countries continues to expand, the need for close monitoring of worldwide test activities becomes an intriguing technical challenge. Ideally, should time allow, a sophisticated data collection capability would be designed and developed that would definitively answer test monitoring requirements. However, time is a luxury that none can afford and therefore current and pending capabilities must be investigated in terms of their utilities.

Phase I of this study focuses on those unclassified and classified imaging sensor products that can now, or may soon, be brought to bear on the monitoring problem in order to determine the feasibility of using such data to supplement or answer specific requirements. Since the products may be acquired on hardcopy (film) or softcopy (digital tapes), means

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Several imaging sensor products were analyzed independently and jointly to document their unique characteristics and to assess their utility for supporting nuclear test monitoring. Those techniques that showed considerable promise were the precise superpositioning of data from multiple sources, the stereoscopic viewing of multiple mission and sensor products, and three-dimensional mapping of multiple image sets.

Phases II and III of this effort will further delineate the sensor suite necessary to accurately monitor nuclear testing and develop a versatile workstation with documented, useful procedures for fully answering the nuclear test monitoring requirements.

Keywords: Digital Image Processing, Radar Imagery, Thermal Imagery (AU)

PREFACE

As the nuclear family of countries continues to expand, the need for close monitoring of worldwide test activities becomes an intriguing technical challenge. Ideally, should time allow, a sophisticated data collection capability would be designed and developed that would definitively answer test monitoring requirements. However, time is a luxury that none can afford and therefore current and pending capabilities must be investigated in terms of their utilities.

Phase I of this study focuses on those unclassified and classified imaging sensor products that can now, or may soon, be brought to bear on the monitoring problem in order to determine the feasibility of using such data to supplement or answer specific requirements. Since the products may be acquired on hardcopy (film) or softcopy (digital tapes), means to integrate them were investigated. This required that the digitizing of film and paper products be analyzed in terms of timeliness and fidelity as well as means to reproduce the derived digital results on high quality hardcopy.

Several imaging sensor products were analyzed independently and jointly to document their unique characteristics and to assess their utility for supporting nuclear test monitoring. Those techniques that showed considerable promise were the precise superpositioning of data from multiple sources, the stereoscopic viewing of multiple mission and sensor products, and three-dimensional mapping of multiple image sets.

Phases II and III of this effort will further delineate the sensor suite necessary to accurately monitor nuclear testing and develop a versatile workstation with documented, useful procedures for fully answering the nuclear test monitoring requirements.

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SECTION 1 -- INTRODUCTION/BACKGROUND

For the past four years, the world has been experiencing the era of "glasnost" and "perestroika" which has lessened tensions between the world super powers and has changed the philosophy and direction of this country's intelligence collection strategies. United States scientists and military personnel are currently provided access to many sensitive Soviet installations which, until recently, were never officially professed to exist. Further, plans are now underway to share the monitoring of activities at both U.S. and Soviet sites where underground nuclear testing is being conducted. Such openness, though constructive, can lead to a false sense of security and a subsequent lack of priority for supporting overhead monitoring procedures. Such a de-emphasis of remote sensing may neither be technically optimal nor cost effective. This potential for relaxing technical intelligence research/operational efforts, and the possible reprioritization of overhead collections against nuclear facilities now available to U.S. scientists, is based on the following tenuous assumptions:

1.1 THE SOVIETS WILL NOT ATTEMPT COVERT TESTING AT MONITORED SITES

Overt or covert testing does not equate to actual covert detonations. Thus, although seismic monitoring will detect most detonations, they may not detect all covert tests. Further, Soviet-provided data on the intent or yield of recorded tests may be subject to conventional Soviet disinformation policies. Unequivocal test data, regardless of its origin, is an exception rather than the rule. Ambiguities will occur even in recorded data which will dilute any positive proof of possible violations. This is especially true if a comprehensive historical data base of the site is unavailable, critical information is incomplete or intentionally ambiguous, and/or if the monitoring of the test has been adversely impacted by political or cost factors. As an example, incomplete documentation of payload decoupling techniques may significantly distort test yield estimations derived from seismic information and therefore may be used to conceal intentional test violations.

1.2 OTHER COUNTRIES WILL NOT CONDUCT COVERT NUCLEAR TESTING

The number of countries which have the potential to produce nuclear detonations is constantly growing and few of these nations allow unconditional monitoring of their test events. As countries and facilities proliferate, the need for identifying these sites and the more accurate overhead monitoring of nuclear tests will become evident. Furthermore, with each successful observation, the disincentives for attempting covert tests will become obvious.

SECTION 2 -- PURPOSE OF THE STUDY

The goal of this SBIR is to determine whether deep, underground nuclear detonations can be detected and validated through the development and use of pragmatic tools designed to exploit the products from current and pending overhead imaging sensors.

SECTION 3 -- SBIR SCOPE

This research investigates the capability and utility of precisely fusing and correlating data from current and near-term multiple collection sources to support collection strategies and the development of processing and exploitation tools to detect and/or verify nuclear underground test results.

Phase I of this study effort investigates the capability of using available overhead sensor resources to detect covert underground nuclear testing throughout the world. Both classified and unclassified products are researched and their results integrated into the analysis. In order to provide for maximum distribution, the study final report will be unclassified but will contain an independent classified appendix which will have more limited distribution. This Phase I project lays the basis for Phase II data handling system design, development, and demonstration using all-source imagery along with advanced softcopy imagery exploitation and data fusion techniques.

SECTION 4 -- STUDY ANALYSIS

4.1 HISTORICAL INTERPRETATION TECHNIQUES

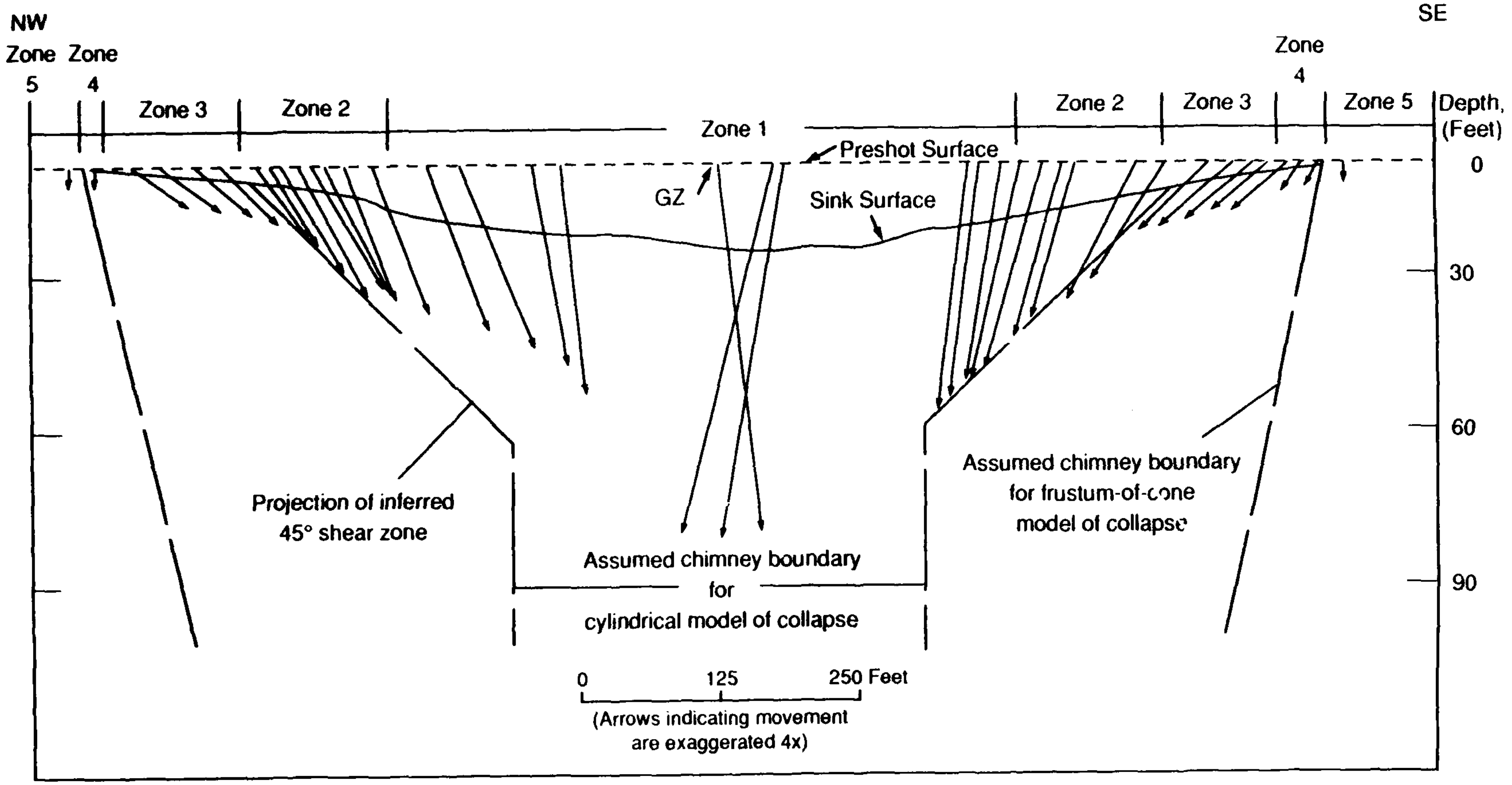
The United States has been conducting contained underground nuclear tests at its Nevada Test Site (NTS) since 1957, a year before the voluntary moratorium on atmospheric testing and six years before the signing of the Limited Test Band Treaty in 1963. Well over 600 underground tests have been executed at this site to date, and there is considerable historical data on the surface effects observed from each of these tests. However, much of the documentation has been through human observation and ground-based photography. More recently (1980s), aerial photographs have been used to map and to document the volumetric and fracture pattern data of collapse craters. Illustration 1, excerpted from Garcia's study,[1] depicts the detailed analyses that have been conducted on historical Yucca Flat subsidence craters. Through the 1970s and 1980s, the U.S. Defense Nuclear Agency (DNA) has also been producing high explosive tests aboveground and under shallow overburden to simulate the blast and thermal effects of nuclear detonations. From both of these efforts several indicators, which can be documented through overhead imaging sensor products, provide data on the intent of the test and the yield of the detonation. A chronological review of such data provides a scenario that allows an analyst to detect the initiation, intent, and progress of the test and predict when the event will occur.

Preparations for actual or simulated nuclear tests are extensive and time consuming. Throughout these activities, certain key ground scars and/or equipment can be observed that provide clues to the intent of the test. A generic timeline, generated under this study, for both aboveground and underground tests is shown in Illustration 2. Keys which allow the analysis of nuclear test preparations at each designated milestone have been appended to the generic timeline. These keys have been extracted from experimental data compiled on numerous U.S. nuclear tests and from actual participation at several DNA simulated nuclear experiments.

---

[1] M.V. Garcia, U.S. Geological Survey, USGS 474-41, NTS216, August 1989.

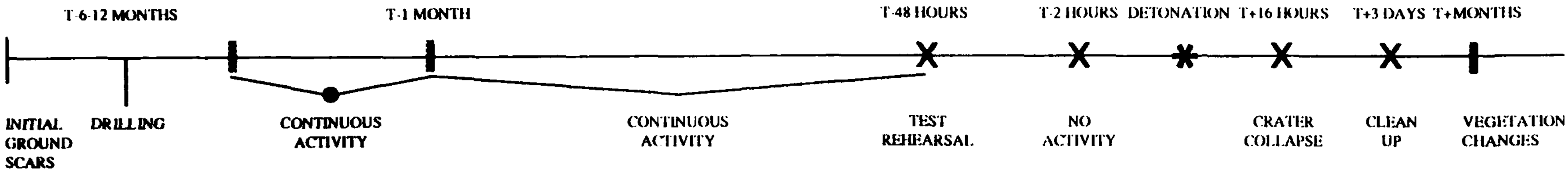
Illustration 1. Surface Displacement in a Typical Sink of Moderate Relief, East-Central Yucca Flat



M.V. Garcia
Department of the Interior
United States Geological Survey
USGS-474-41
NTS-216

SBR04

Illustration 2. Generic Testing Time Line



OBSERVABLE SURFACE KEYS

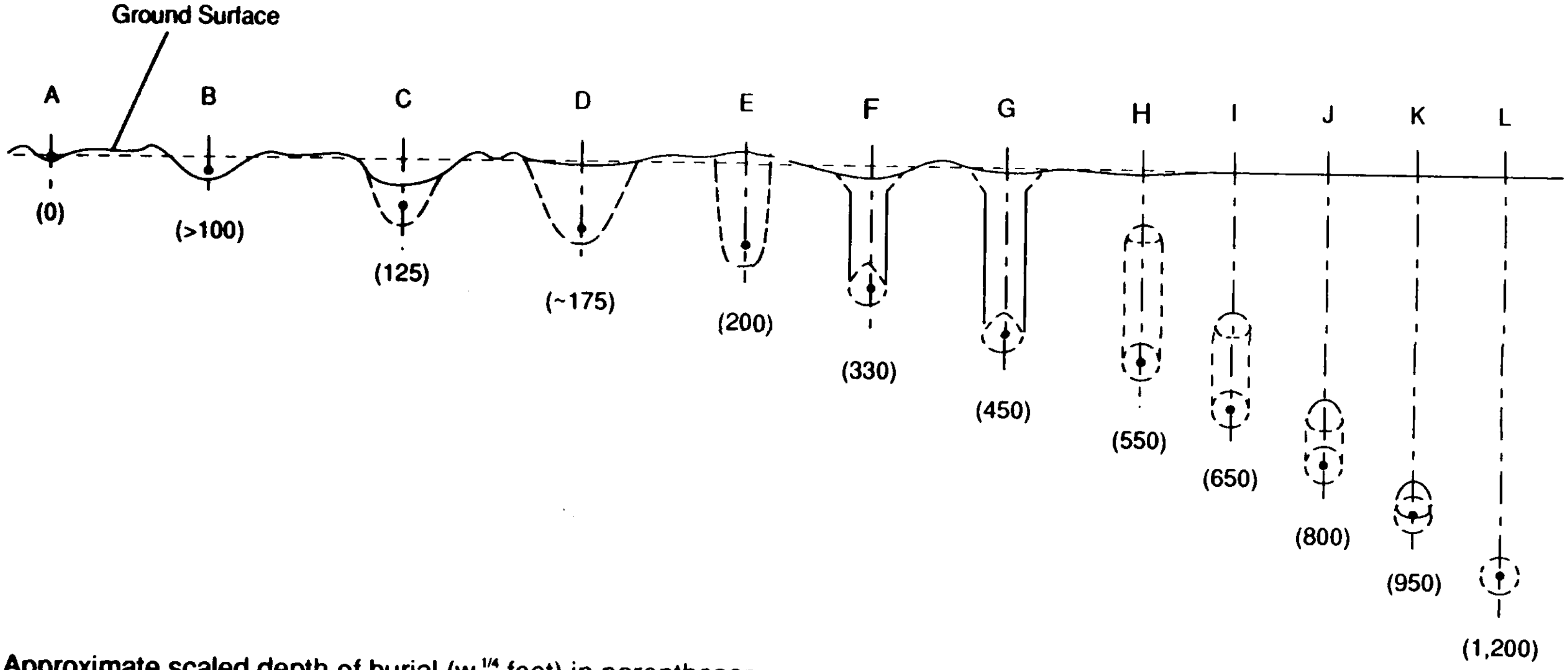
[illegible]	[illegible]	T-1 MONTH TO T-48 HOURS	T-48 HOURS	T-2 HOURS	*	T+16 HOURS	T+3 DAYS	T+ MONTHS
SITE ISOLATION GROUND SCARS NEW ROADS DRILLING APPARATUS DRILLING CORES/CASINGS SPOIL PILES SECURITY CONTROLS SURVEYING	DRILLING APPARATUS DIGGING APPARATUS CABLE LAYING IN TRENCHES CONSTRUCTION OF UNDERGROUND STRUCTURES TESTING EQUIPMENT GENERATORS & BUNKERS PHOTO SUPPORTS & MARKER PYLONS EXPLOSIVE HANDLING FACILITY CONSTRUCTION OF CHARGE CONTAINER COVERING CABLE TRACES	COMPLETION OF CHARGE CONTAINER ARRIVAL OF EXPLOSIVE COMPONENTS SPECIAL TARGETS ARRIVE & ARE EMPLACED INCREASE IN PERSONNEL & POV'S. SECURITY PERIMETERS ON TEST BED (CHAIN LINK & CONCERTINA WIRE) GUARD SHACKS AROUND SITE PREPARATION OF EXPLOSIVE AT HANDLING FACILITY LOAD EXPLOSIVE INTO CONTAINER INSTALL CAMERAS ON PYLONS MAXIMUM TRAILERS & SUPPORT EQUIPMENT ON TEST BED COVERING UNDERGROUND STRUCTURES	TEST AREA CLEAR MAX NUMBER OF PERSONNEL WX BALLOONS IN PLACE DUST COLLECTING MISSILES REMOVAL OF TRAILERS & SUPPORT EQUIPMENT SPECIAL AIRCRAFT AT NEARBY AIRFIELDS	TIGHT SECURITY NO ACTIVITY WX BALLOONS LAUNCHED VIP KEYS (SPECIAL TRANSPORT) ROAD BLOCKS	DETONATION DEBRIS DEBRIS CLOUD VENTING DUST AIRCRAFT MISSILES	PERSONNEL ON SITE VEHICLES AT SITE DEBRIS FRACTURES CRATER SPALLING EQUIPMENT DAMAGE FAULTING SOIL TEXTURE CHANGES CAMOUFLAGE (D&D)	TEST BED CLEAN UP VEHICLES PERSONNEL SURFACE SUBSIDENCE TRAILERS & SUPPORT STRUCTURES IN PLACE RECOVERY OF EXPERIMENTS EXCAVATION AT U/G STRUCTURES WITHDRAWING TRAILERS & SUPPORT EQUIPMENT	VEGETATION CHANGES DRAINAGE CHANGES SUBSIDENCE EXCAVATION OF U/G EX-PERIMENTS EXCAVATION OF CRATER FILL IN CRATER

The type of detonation can be determined by the various surface effects produced -- assuming that the subsurface geology of the site is known. As an example, aboveground simulated nuclear tests and those under shallow overburden produce characteristic ejection craters, the size and depth of which are dictated by the force of the detonation and the geology of the area. The following schematic (Illustration 3) depicts the predicted generic shapes of both ejection and subsidence craters in alluvium similar to that at the Nevada Test Site and the White Sands Test Range.[2] Notice that the ejection craters have a definite lip composed of ejecta, whereas the subsidence craters do not show such features. At "E" in the illustration is a rubble-filled cavity that actually produces a mound called a retarc (crater spelled backwards). In order to delineate better between ejection and subsidence craters, the following analysis is provided. Illustration 4 shows the ejection crater created during the DNA Misty Picture aboveground simulated nuclear test conducted at the White Sands Test Range in May 1987. This image was collected by a low-flying F-14 aircraft using a T-11 frame camera loaded with high spatial resolution BW film. The crater is approximately 100 meters in diameter and 25 meters deep. The ground resolution of the imagery is approximately 0.5 meters. The prominent crater lip, flat bottom surface, and a well-defined debris pattern surrounding the crater provides irrefutable evidence that this is an ejection crater. Note also the lack of radial fracturing within the crater. Illustration 5 is a daytime thermal image of the same crater. The image was acquired three hours after detonation, by a low-flying RF-4B aircraft equipped with an AAD-5 thermal scanner collecting in the 8-14 micron region of the spectrum. The spatial resolution of this image is about 0.5 meters and the relative thermal resolution is approximately one quarter of a degree centigrade. The lighter the tones within the image, the hotter the relative temperature of the objects. Notice that both the bottom of this crater and the surface of the surrounding desert are hot (but for different reasons). It is interesting to note the amount of detail that can now be acquired on the dark (cool) distribution pattern of the ejected material beyond that which can be observed on the higher spatial resolution optical scene (compare with previous Illustration 4). Again, no radial

---

[2] M.V. Garcia, U.S. Geological Survey, USGS 474-41, NTS216, August 1989.

Illustration 3. Generalized Gradation in Cratering and Initial Collapse Effects Resulting from Explosions of the Same Yield at Selected Depths of Burial in Alluvium, Nevada Test Site.



Approximate scaled depth of burial ($w^{1/4}$ feet) in parentheses

* Department of the Interior
United States Geological Survey
USGS-474-41
NTS-216, 8 Aug 1989

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Illustration 4. Misty Picture Crater (Panchromatic Film Camera Product)

Illustration 5. Misty Picture Crater (Thermal Sensor Product)

[redacted]

fracturing can be observed in the crater. Thus, there can be no doubt that this is an ejection crater. Illustration 6 provides an image acquired from a low-flying RF-4B using the APD-10 Side Looking Airborne Radar. This is an X-band radar with a spatial resolution on the order of five meters. Even at this relatively low spatial resolution (compared to optical), the crater lip and debris pattern delineates this as an ejection crater. The advantage of this collection technique is that the crater can be detected and defined regardless of cloud cover or ambient light conditions.

For comparison, Illustration 7 depicts known subsidence craters within the Nevada Test Site. The imagery was acquired by a high-flying aircraft for the National High Altitude Program (NHAP). The camera is a WILD RC-10 that used high spatial resolution black and white film. Note that none of these craters have the lip structures shown on previous illustrations but have steep conical shapes with a sharp apex. Radial fracture patterns can be observed in the larger craters, and although ground scarring has occurred around the sites, this manmade activity can be easily differentiated from the debris patterns that occur around ejection craters. Illustration 8 shows SEASAT coverage of the Nevada Test Site. SEASAT was a space-based "L"-band Synthetic Aperture Radar orbited in 1978. Its spatial resolution is on the order of 38 meters. Note that even at these spatial resolutions, since they do not have prominent lips or debris patterns surrounding them, it is still easy to discern that the craters are due to subsidence.

Obviously, there are many underground tests that do not form craters and the tools necessary to detect such activities must be more sophisticated to identify the subtle surface changes that may occur. In order to maximize the amount of data that can be analyzed and enhance its visibility, it will be necessary to combine the products from several sensors in unique ways to bring out the subtle differences that may be recorded in different parts of the electromagnetic spectrum. This correlation and fusion of multisensor imagery and collateral data is the purpose and thrust of this SBIR. Means to accomplish such tasks have been recently enhanced through the

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Illustration 6. Misty Picture Crater (Radar Sensor Product)

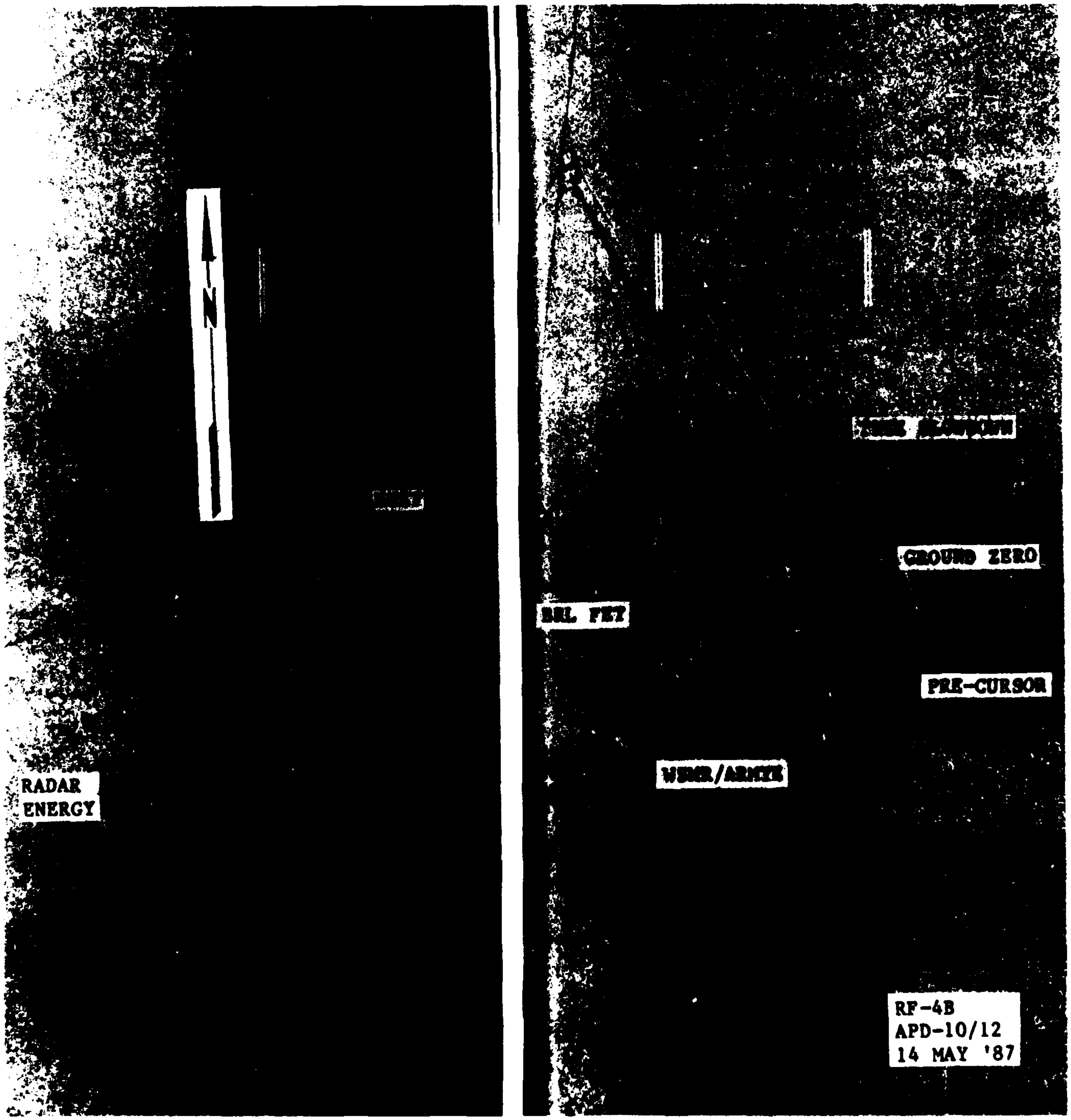


Illustration 7. NHAP BW of NTS Subsidence Craters

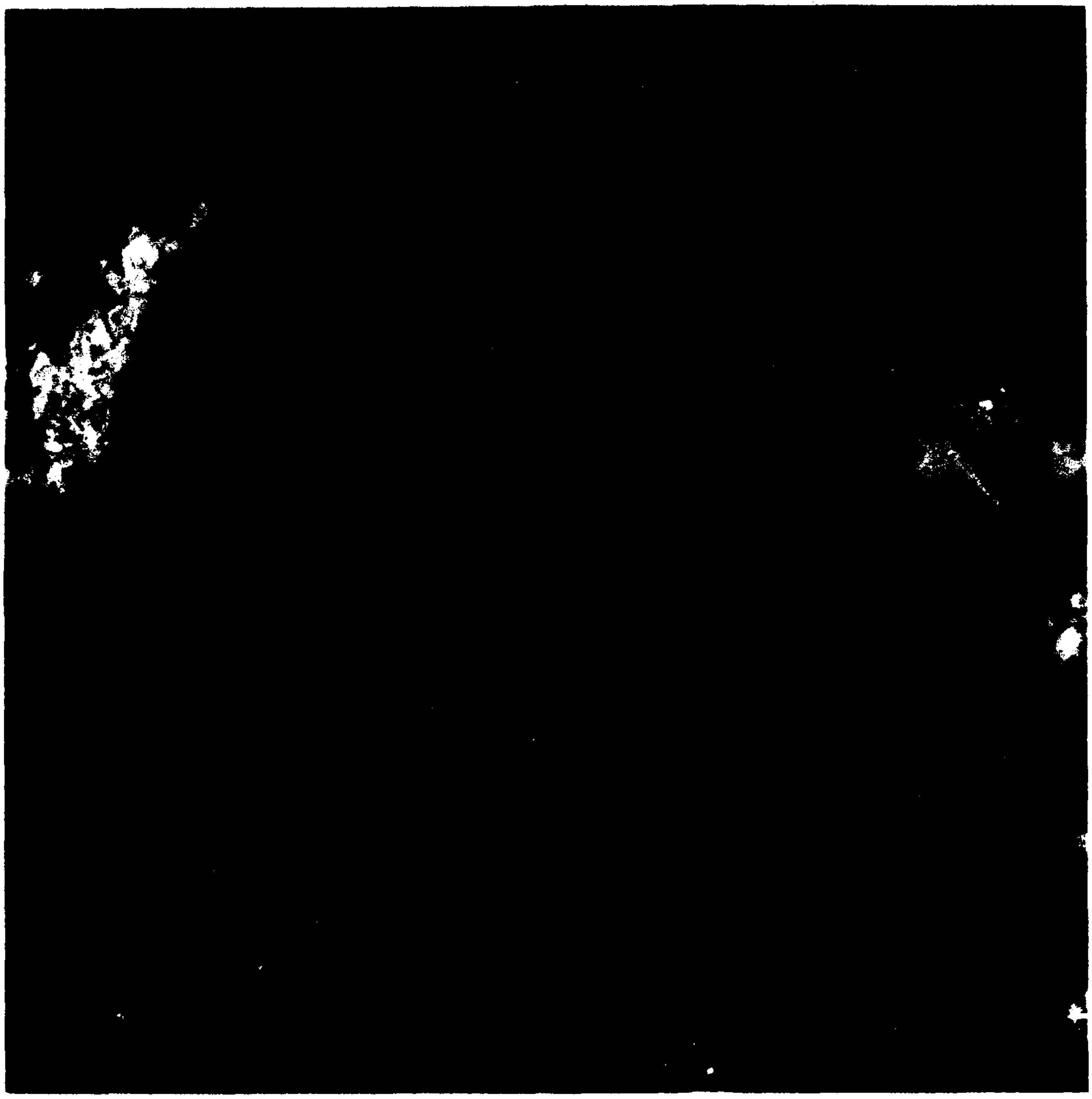
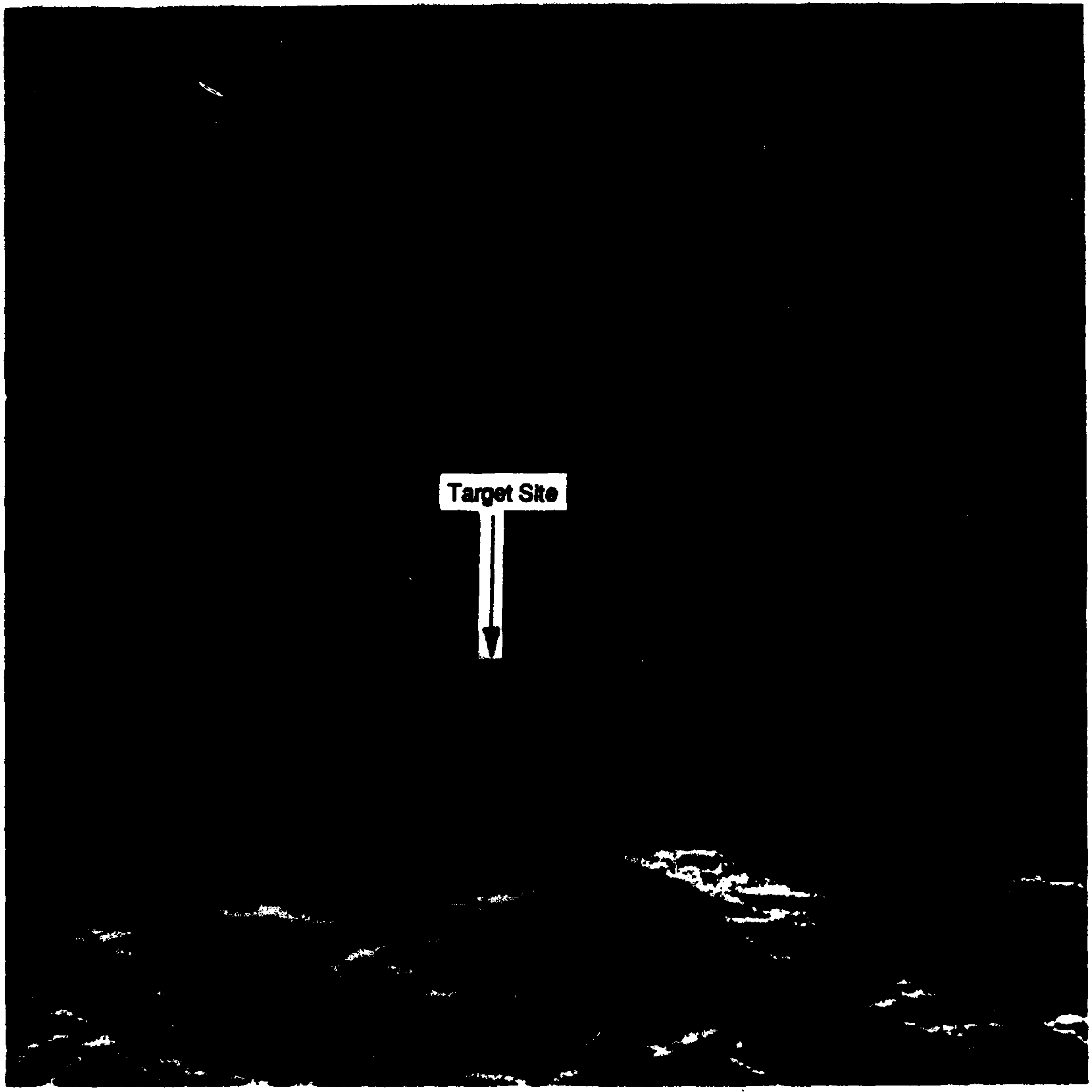


Illustration 8. SEASAT Coverage of NTS



improvements that have occurred in the digitization of hardcopy film products, in digital image processing and photogrammetric techniques that allow for the precise registration of multiple products, one upon the other.

4.2 TARGET SITE SELECTION

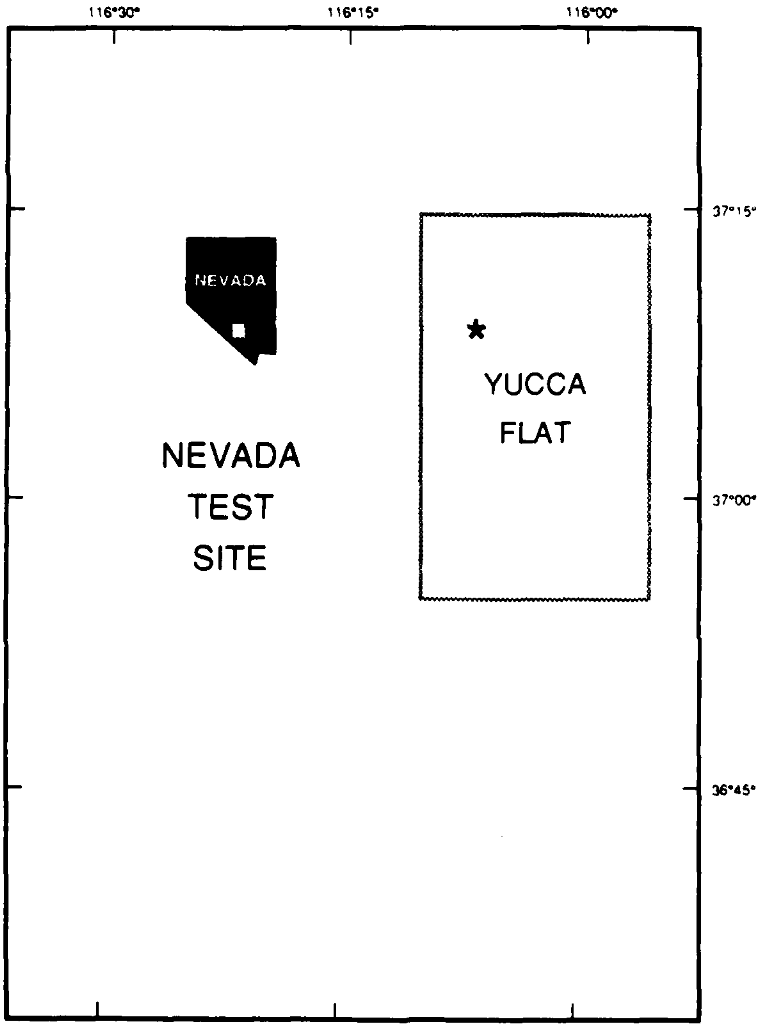
After considerable research, the U.S. Nevada Test Site (NTS) was selected for study (see Illustration 9). The decision was made primarily because of the extensive amount of historical and current data that could be compiled concerning site activity. Available collateral data included detailed descriptions of tests, ground photography, historical and current topographic maps, as well as detailed historical geologic maps of the region. Since much of this study was concerned with the exploitation of imagery, targets within the site were reviewed and selected based on the availability of imaging sensor products. Therefore, the target area for the unclassified portion of this study was selected at coordinates 37°08'N, 116°08'W, the site of several tests that produced subsidence craters and other evidence of test activities. Available collateral data concerning the site included:

- Historical data of the "Pod" test (10/29/69)
- 1:24,000 scale geologic map (circa 1963)
- 1:24,000 scale topographic map (circa 1986)
- 1:100,000 scale topographic map (circa 1979)

Imagery that was accessible included:

- Point Position Data Base (1977)
- SEASAT (1978)
- NHAP Black and White (1983)
- NHAP Color Infrared (1983)
- Landsat Thematic Mapper (1984)

Illustration 9. Nevada Test Site



★ - **Target Area**

4.3 HISTORY OF THE TARGET AREA

The Nevada Test Site was established as an entity in 1950. Geographically located in an isolated area near the southernmost corner of Nevada, adjacent to the California border, this area of approximately 1,350 square miles was set aside as a government facility dedicated to nuclear research and testing. Approximately 600 square miles was designated for actual testing, whereas the remainder was used as a buffer for isolation and for the construction of support facilities. From the year 1950 through 1957, numerous atmospheric nuclear tests were conducted. However, in 1957, based on safety concerns over nuclear pollution as well as anticipated global restrictions, U.S. nuclear testing was taken underground. In 1958, the U.S. voluntarily agreed to a moratorium on atmospheric tests, anticipating by five years the 1963 Limited Test Ban Treaty. Since the 1950s, well over 600 tests have been conducted in the area. The test site remains active with several underground tests being scheduled in the 1990 time frame, some to be monitored by Soviet scientists at the site itself.

The selected target area for this study includes the site of the "Pod" test. This test event occurred during October 29, 1969, at a depth of 1,025 feet in tuff overlain with river alluvium, resulting in the creation of a large subsidence crater that can be observed on all imagery reviewed during this study. The coordinates for the site are 37°08'07"N, 116°08'09"W and its position within the NTS is depicted on Illustration 10.

4.4 GEOLOGIC SETTING OF THE TARGET AREA

The selection of a viable nuclear test site requires that a number of critical factors be taken into consideration. First and foremost are those parameters that apply particularly to the continuing safety of the surrounding populace and of test facilities/personnel, both in terms of unforeseen ground shock and atmospheric or groundwater contamination. Thus, the initial criteria require that large isolated tracts of terrain be dedicated to this unique research far from lines of communication or transportation and surrounded by such conventional safety measures as fencing and monitoring by electronic measures, as well as guards. Geology is also a critical factor

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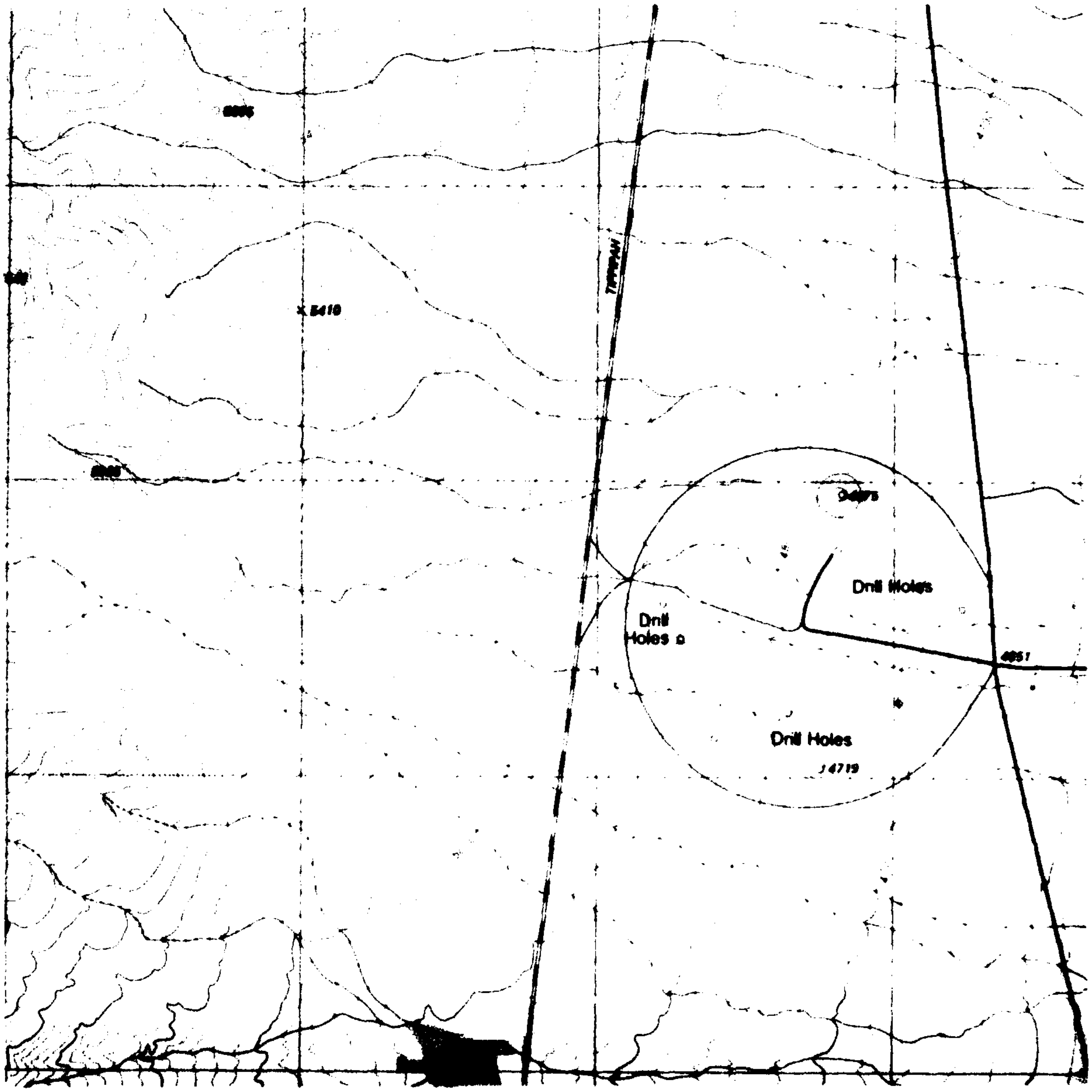
Illustration 10. Topo Map of Target Site



since it will play an important part in bounding the potential for subsurface water contamination and unintentional venting of nuclear contaminants into the atmosphere. Geologic requirements that impact upon economical and valid test results also restrict the selection of a good site.[3] Ideally, the rock medium must be soft and dry to assure that the drilling of shafts and adits can be conducted economically and that seismic shock waves will be absorbed within the perimeters of the test site. The rock medium should be homogeneous and chemically inert to the tested materials, yet be structurally isolated and sound to reduce (but not distort) the transmission of seismic shock waves. Finally, a variety of geologic formations should be present within the site to allow for testing within selected geologic settings.

Most of these criteria are met within the Nevada Test Site where surface alluvium of stream sand and gravel assume considerable depth underlain by unconsolidated or welded tuffs, shale, sandstone, and quartzite. Detailed geologic maps at scales of 1:24,000 are available for all parts of the Nevada test range. Of note is the extensive number of active fault lines that traverse the area, many of them kept active by the underground testing that occurs periodically.

4.5 CURRENT IMAGERY INTERPRETATION TECHNIQUES

In conjunction with conventional photointerpretation techniques, in which an interpreter analyzes and reports upon his results derived by viewing images on light tables or digital display devices, new hardcopy and softcopy tools have been developed that enhance the capability to conduct comprehensive analyses by precisely combining multiple sources of information. Such processes have evolved because of the multiplicity of imagery products that are now available to the analyst. This study documents the utility of two of these advanced processes being pioneered at Autometric:

---

[3] F.N. Houser, "Application of Geology to Underground Nuclear Testing," Nevada Test Site," USGS Federal Center, Denver, CO, 1968 (Excerpt and from Geologic maps of the area).

1) The digitization of imagery and map data, the use of multiple digital images, and state-of-the-art digital image processing techniques to support the required analyses; and

2) The precise superpositioning of collateral data derived from multiple sources upon three-dimensional stereoscopic images, viewed through the optics of a light table or a stereo image analytical plotter.

Illustration 11 shows the Autometric APPS-IV (Analytical Photogrammetric Processing System) that was used to support this research project. This instrument was combined with a Lexidata display system to document the data digitized on the APPS-IV for superpositioning upon other products being analyzed. Illustration 12 depicts a simplified example of its output derived by using the Nicolet Multicolor Plotter Model Zeta 836. This data was produced from an NHAP image over a portion of the Nevada Test Site and precisely outlines and positions several craters of interest. It can now be scaled and precisely superimposed over other imagery and viewed in three dimensions through the optics of the APPS-IV.

Illustration 13 depicts a geologic map that was digitized, digitally enhanced, and reproduced to indicate the quality of the digitized product. The hardcopy outputs from digitized material were created for this study through the use of a 3M prototype Color Laser Imager (CLI), now driven off a VAX 11/780, which will be on the market in late 1990. The quality and flexibility of this instrument makes it a likely candidate as an output device for low cost digital workstations. Since the digitized data is now stored in a computer, it can be displayed and precisely superimposed upon a number of other digitized or digital products. This study examined the ability of combining such digitized data with digital imagery.

4.6 DIGITAL IMAGERY ANALYSES

4.6.1 General

Since the only original digital product covering the target site and readily available for this study was the SEASAT data, all the other

Illustration 11. APPS-IV Analytical Plotter

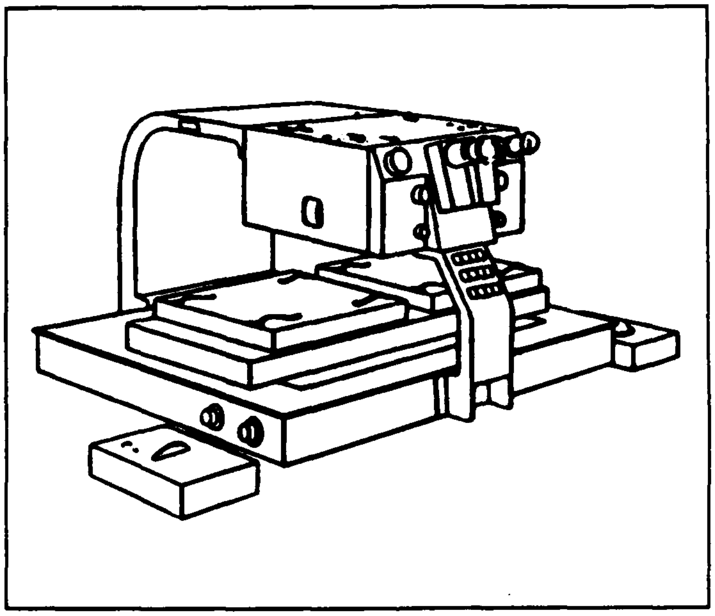


Illustration 12. APPS-IV Product

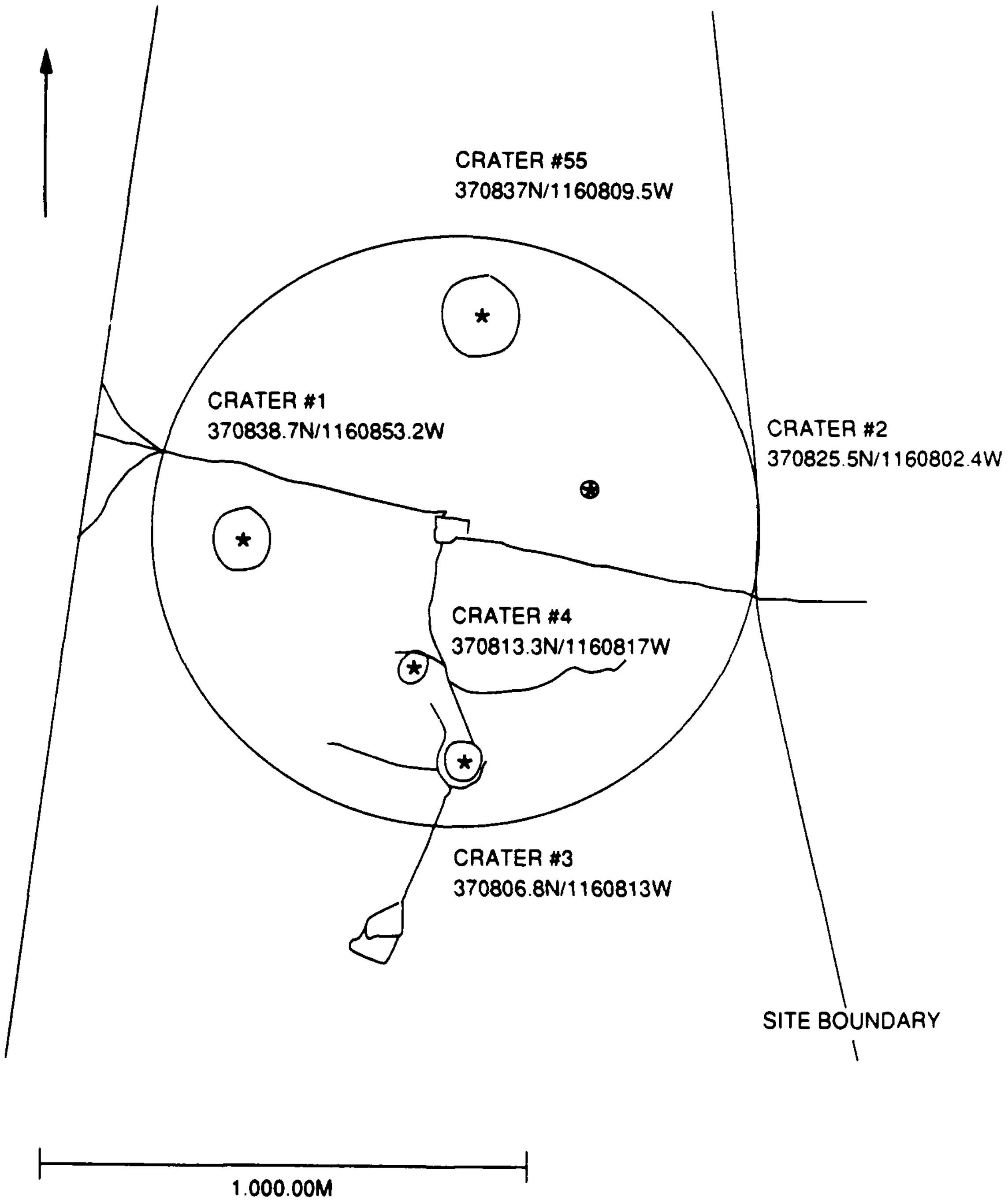


Illustration 13. Digitized Geologic Map of Target Site

collected photography was digitized using the Howtek linear scanner operating at a maximum resolution of 300 dots per inch. The digitized data was then stored in a VAX 11/780 and initially displayed on a COMPAQ 386 using ERDAS software. This allowed an operator to conduct not only conventional digital image enhancements but to superimpose digitized collateral or other imagery using a variety of techniques. The following are analyses and comments of imagery analysts concerning the method of reviewing each product and the utility of digitally combining each of the data products.

4.6.2 Point Positioning Data Base (PPDB)

This imagery was acquired from the Defense Mapping Agency as a photographic product and digitized using the Howtek scanner. Imagery analysts subjectively compared the digitized product to a second-generation film transparency and concluded that there was a small loss in spatial resolution due to the digitization and display process, but not sufficient to significantly influence the results of their analyses. As the imagery analysts worked closely with the image processing analyst (a key requirement for image exploitation RDT&E), they recognized and commented favorably on the flexibility of being able to overlay collateral data, quickly and precisely, and the usefulness of digitally enhancing the imagery. It was determined by viewing the entire PPDB frame that the spatial resolution of both the transparency and the digitized imagery is on the order of two meters. As an example, a large vehicle (such as a diagnostic laboratory van) could be identified; smaller, privately-owned vehicles could only be detected in recognizable parking areas. This PPDB coverage occurred in 1977 and there appears to be no on-going activity at the selected target site. However, one large subsidence crater on the north side of the site, a medium-sized crater on the west edge, and two small subsidence craters on the south side, could be identified (see Illustration 14 upper left corner). By superimposing the 1986 digitized topographic map over the target area on the PPDB imagery, it was determined that the other surface scars were previous drill holes or old test sites. Microdrainage patterns could be documented as well as landslides and many fault lines. Primary roads were easily observed; however, only a few remnants of tracks show up within the circular perimeter of the target area. A road can be observed traversing from the west edge of the perimeter towards

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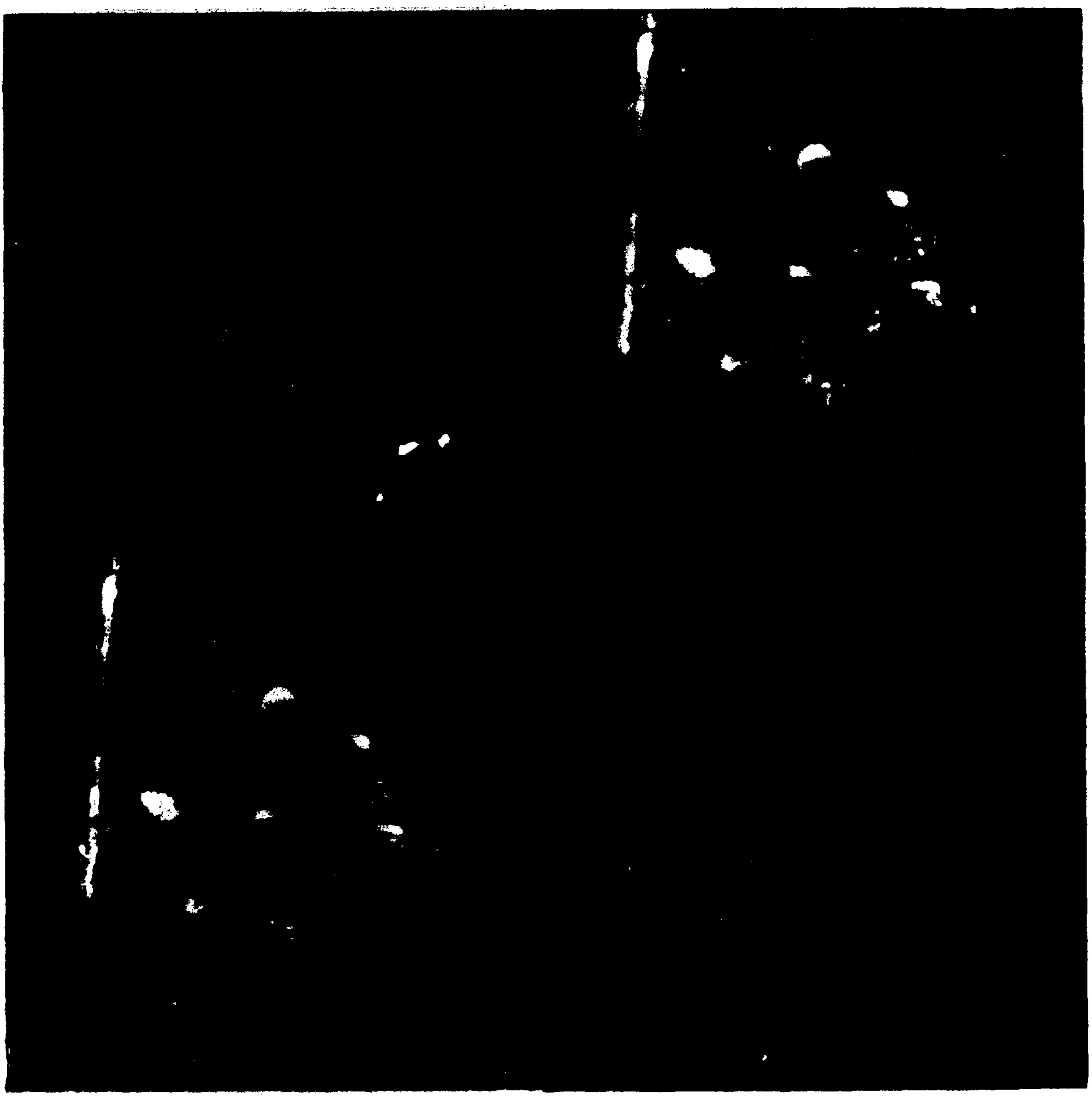
Illustration 14. PPDB Enhancements



its center and then north to the large subsidence crater. Evidence of other trail scars go from the center of the target south toward the two small subsidence craters. The conclusion that no activity was occurring is based upon the lack of new scarring and the lack of test equipment/vans. No spalling or changes in desert varnish could be observed, probably due to the low level of activity. However, it would be questionable if such evidence could be definitively detected at PPDB spatial resolutions.

Several conventional digital image enhancement techniques were tested in attempts to bring out added information. Although the ERDAS software was developed to exploit multiple-band data, it was found helpful for supporting the analysis of any digital image product. Among the various enhancement techniques that proved useful are those depicted on Illustration 14. In the upper left hand corner is the unenhanced PPDB data as viewed on the digital workstation. Note that the PPDB has a grid to support its use for precise mapping. Reviewing the histogram of densities acquired throughout the target area, the superfluous data were clipped from either end of the density range and a linear stretch enhancement to two standard deviations was produced on the remainder. The results are depicted in the upper right hand corner of Illustration 14. This enhancement allows the analyst to document more confidently the various scars, the perimeter road, and terrain changes. However, because of the limited dynamic range of the original transparency, it is not possible to bring out much additional data in the bright, highly saturated areas. This image was also enhanced using a three-by-three filtering technique to emphasize edges. The result is depicted in the lower left corner of Illustration 14. Note how linear edges are significantly sharpened (e.g., the roads, the grid itself, and the crater perimeters). However, this process did add significant background noise that was distracting during the initial analysis. It did not appear to bring out additional fault or spalling information. Finally, the lower right corner of Illustration 14 shows the utility of clustering density levels to bring out additional data. Again, this technique is most useful with multiple-band data but also helps support the exploitation of single-band data. In this example, the image was contrast stretched and end points 63-130 on the histogram were loaded onto the red gun of the digital display, end points 10-240 on the green gun, and end points 24-212 on the blue gun. Note that in this pseudocolor the terrain and detail within the bright saturated areas are better delineated. As a result of these analyses, the same techniques were used to support the analysis of all other digitized products.

4.6.3 SEASAT Radar Image

The SEASAT digital tapes were made available for analysis. Coverage of the Nevada Test Site was acquired in 1978 with this 1275 MHz, L-band Synthetic Aperture Radar (SAR) system that achieved spatial resolutions on the order of 38 meters. Although the target site could be identified by the road alignments and the large subsidence crater, very little else could be gleaned from the image (see Illustration 15). Contrast stretching the image did add to the analyst's confidence level so that he could detect the target site and identify one subsidence crater, but he could only have noted a change if that change produced craters as large or larger than the one observed at the site. A second enhancement was attempted which, in effect, mapped the brightness levels within three separate zones. The density histogram was divided into three selected zones that would separate target data from the background. Illustration 16 depicts one of several attempts. In this example, points within the histogram range of 0 to 20 were loaded to the blue gun, points 21 to 41 were loaded to the green gun, and points 42 to 255 onto the red gun. Although the added data was subtle, it did help support the analysis. Additional road detail was brought out, as were other possible test sites. An attempt was then made to detect the presence of small faults in the area by superimposing the geologic fault data onto the enhanced image, but without definitive results. It can be extrapolated that using radar data at these spatial resolutions would only be useful in searching for new sites or monitoring known sites for changes by detecting scars from large test preparations or large subsidence or ejection craters. Its primary attribute would be for searching large areas and for monitoring sites where atmospheric conditions are less favorable for optical thermal, or multispectral (SPOT, Landsat-type), collections. Of course, a higher resolution SAR system such as shown in previous Illustration 6 would be of greater value.

Illustration 15. SEASAT Enhancements

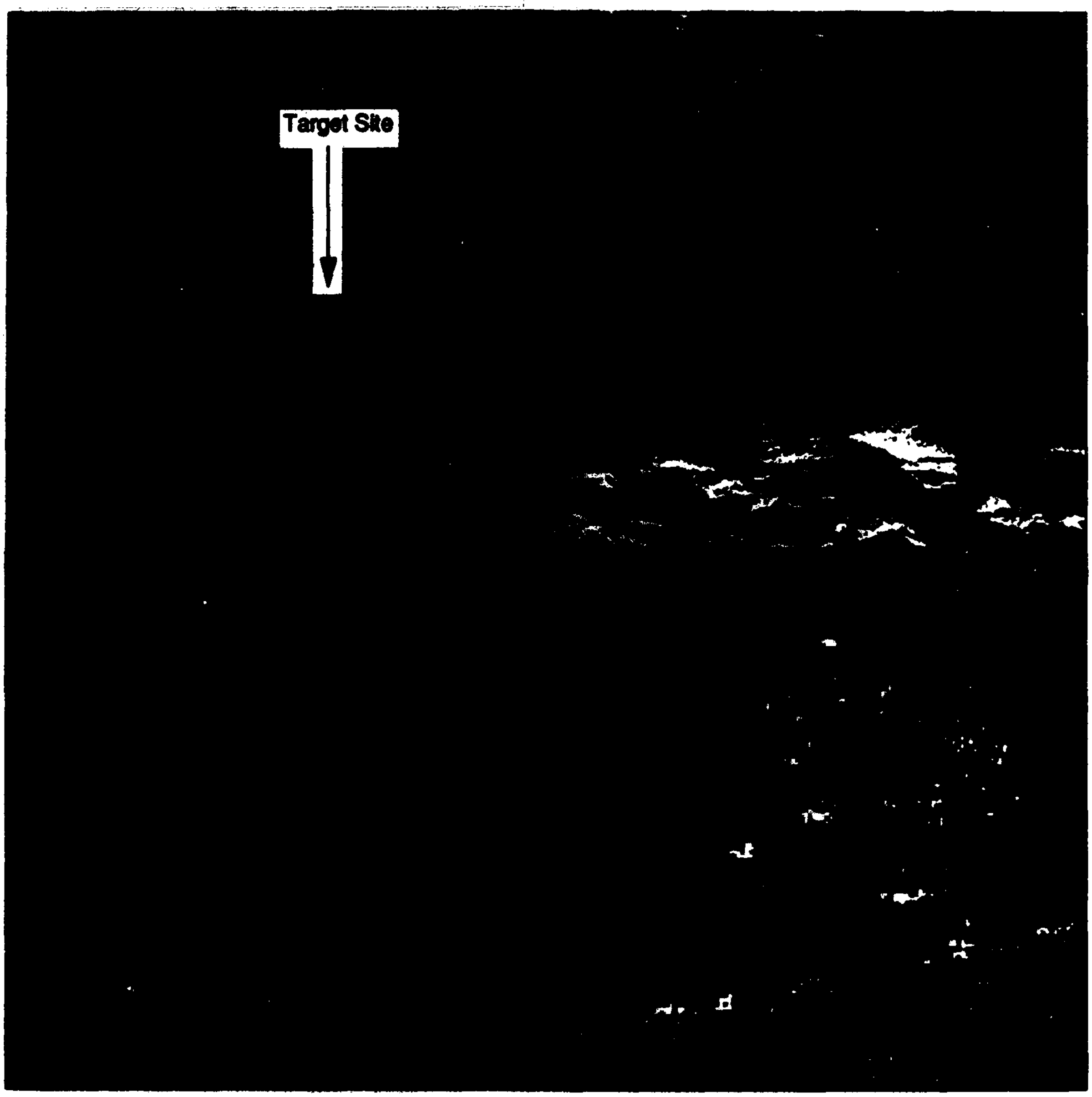
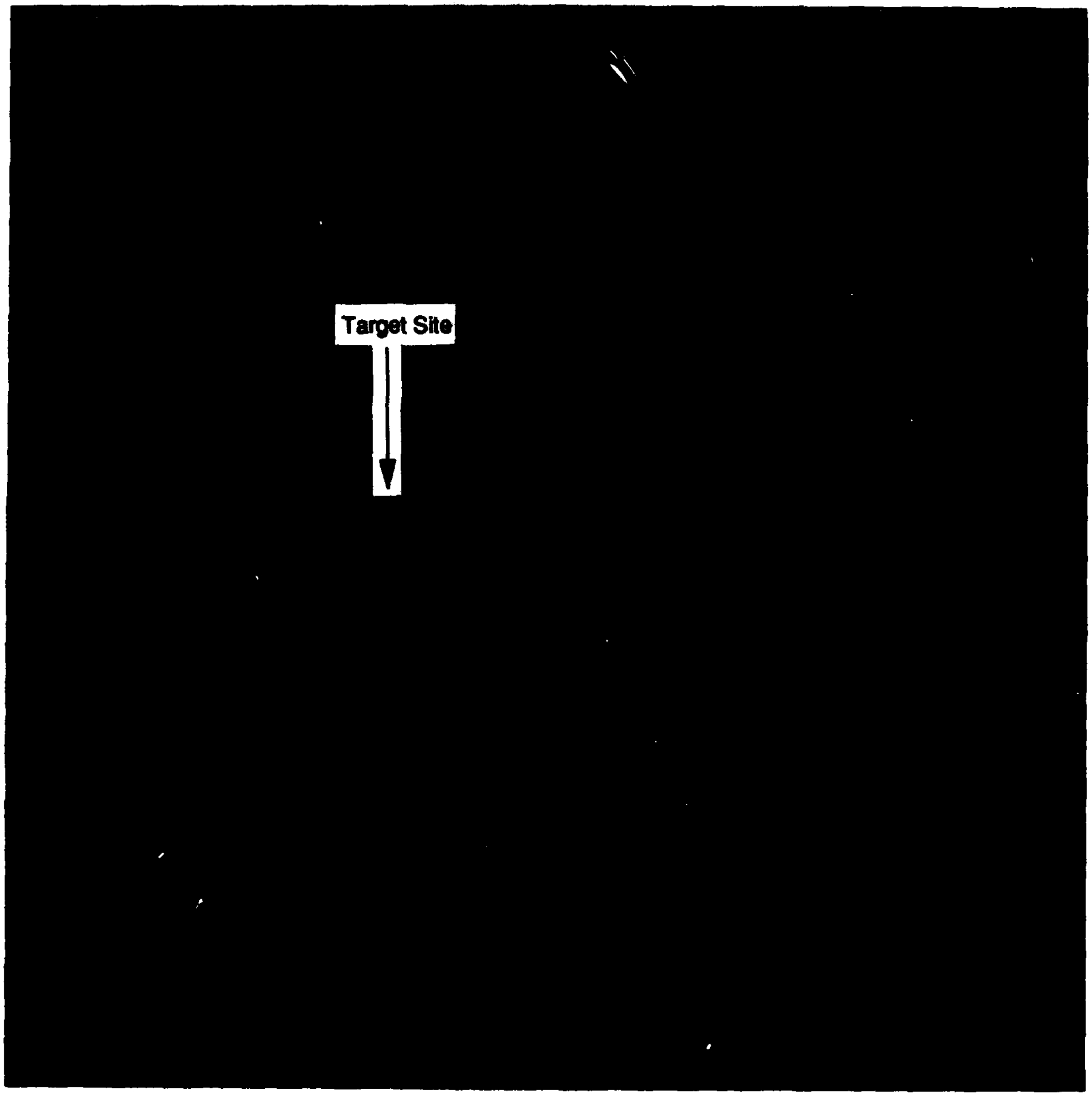


Illustration 16. SEASAT Density Enhancement



4.6.4 NHAP Imagery

In 1983, two National High Altitude Program (NHAP) missions were flown within a day of each other over the Nevada Test Site. One mission collected data on color infrared film (CIR), the other on standard black and white (BW) film. The color infrared product produced the best spatial resolution of all the imagery acquired over the site (approximately one meter). The BW imagery is of slightly poorer resolution. The digitized CIR data were enhanced by contrast stretching to three standard deviations and the three bands were completely correlated. The BW data were also contrast stretched to three standard deviations. The results are depicted on Illustration 17 in the upper right and lower left corners. Aside from spatial resolution differences, note that the CIR provides a much more detailed depiction of the microdrainage patterns than does the BW material or the PPDB products. This is due to the CIR capability for picking up subtle changes in vegetation growing within the drainage channels and the subtle soil reflectivities possibly due to changes in soil moisture. In this instance, the BW products do not appear to provide any additional data to what was acquired by the CIR film. However, at these spatial resolutions, detailed data concerning equipment, cabling and drilling could be identified if the site had been active, and natural changes such as new faulting or landslides could have been identified from both film products. In the short time between the two collections, no apparent changes have taken place. Illustration 17 also shows PPDB data that has been contrast stretched to three standard deviations. Since this data was collected five years earlier than the NHAP material, it provides a good data base for detecting changes, even though its spatial resolution is much poorer. Immediately apparent is the fact that at least one new test either has occurred or is about to begin. A large, new, leveled square test site with a secured perimeter has been developed just south of the largest subsidence crater. One large, prominent, highly reflective rectangular area can be observed and one possible large van is parked adjacent to its northwest corner. The presence of the van indicates that a test may be pending. The 1986 revised topographic map in the upper left hand corner of Illustration 17 depicts the test site as a drilling site, shows the road network to the new site, and how the site development has affected the natural contours in the area. A 1979, 1:100,000 scale

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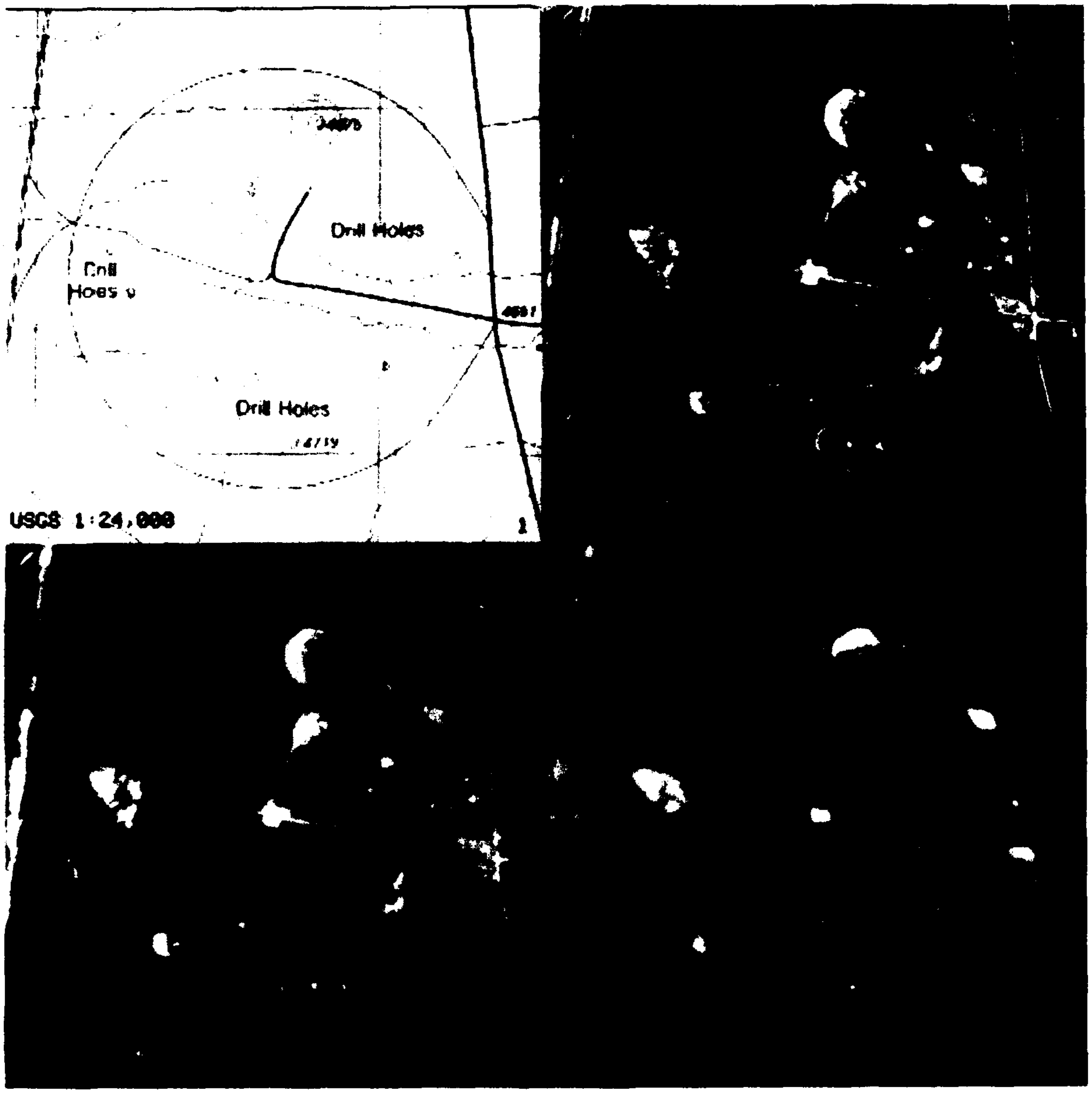
Illustration 17. NHAP Enhancements Compared to PPDB



topographic map of the area did not show the roads to the site. Analysts documenting this data liked the capability of producing the four images on hardcopy for historical support and easy dissemination of the data. They also determined that the digital superpositioning of two types of imagery was too distracting and that split screen or windowed data is much easier to interpret. Flickering between images at different selectable flicker rates and with use of different colors for final presentation of fused data is another technique which will be more fully investigated under Phase II.

The NHAP imagery was acquired for mapping and therefore its stereoscopic quality is excellent. Using split screen techniques, the imagery analysts could view two adjacent frames stereo-optically at the workstation, or from the hardcopy CLI imagery reproduced. Since such techniques have proven useful in detecting changes occurring during the cycle period between frames, it was decided to determine if two frames from different missions, which used the same camera but different films, could be scaled and registered precisely enough to produce a stereo image. Illustration 18 shows the results. Using the stereoscope supplied in the back of this report, note that stereo is achieved and because some of the background noise is canceled out when the eye integrates the two images, the discerned stereo image appears slightly sharper than the best single image and all the data detectable within the sharpest image is now observed in the stereo image. If changes have occurred between the imaging times, then these can be detected by simply blinking each eye as you view the stereo image (similar to the flickering technique mentioned above). Illustration 19 depicts a stereo image produced from two different missions flown with two different cameras and film emulsions. Digital scaling and registration allowed these disparate products to be fused into a stereopair of images. Although the spatial resolution differences between the two products is significant, it did not adversely affect the quality of the stereo image. However, caution must be used in attempting to acquire other than relative height data. Since the first image (the PPDB product) was flown over five years before the acquisition of the NHAP image used in this study, several changes have taken place and can be easily observed. In summary, digitally acquired images from different missions or cameras, can be properly fused into stereopairs that not only

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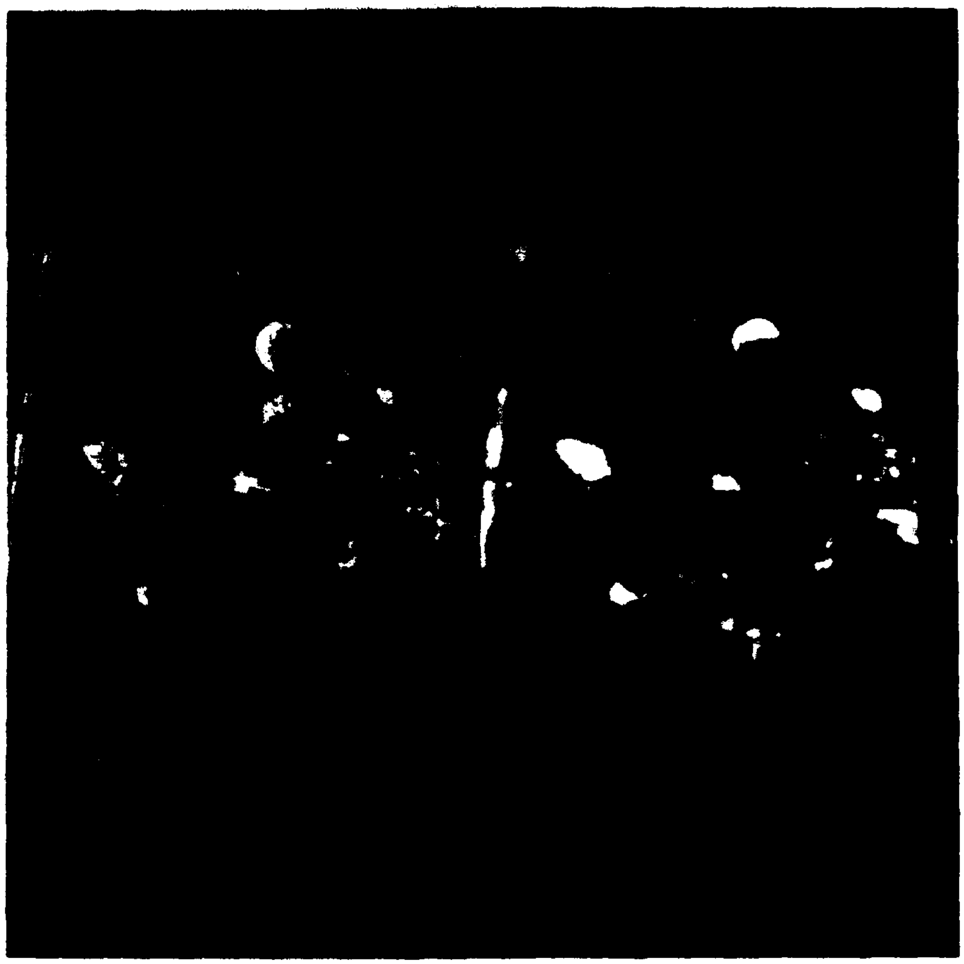
Illustration 18. NHAP Stereo Product

Illustration 19. NHAP/PPDB Stereo Product



provide useful three-dimensional views but are useful tools for observing changes that have occurred between acquisitions.

4.6.5 Landsat Thematic Mapper (TM) Imagery

The only Landsat data available for this study was a 1:100,000 scale image map of Pahute Mesa, Nevada, produced in 1984 by the U.S. Geological Survey. This image map was compiled using only bands two, three, and four of the 30-meter Landsat TM data. The resultant product simulated imagery acquired using color infrared film, which depicts vegetation in various shades of red, depending upon its turgidity (health, amount of chlorophyll, water and carbon dioxide in the vegetation). In supporting this study, the target site was then digitized at 300 dots per inch and displayed in softcopy on the screen for analysis. This provided an excellent overview of the target area and some of the mountainous slopes surrounding it (see Illustration 20). The overview was then compared to the digitized 1963 geologic map to determine whether fault lines and other lineaments could be detected. It was determined that most of the long lineaments could be identified, especially in the mountainous regions to the south-southwest and southwest of the test site. Many of these fault lines appear to be associated with landslide scars and scree (rubble) which were observable on the Landsat TM image. However, since the geologic map did not document landslides, it could not be determined whether these slides were correlatable to specific tests. However, most could be correlated to the 1977 PPDB and the 1983 NHAP coverage, indicating that the initial slides existed prior to these dates. It could not be determined whether the slide scars had grown in size or whether additional scree had accrued. More detail could have been gained if the original digital TM product had been available, since TM bands five and seven were designed to support geologic analyses (Phase II efforts will thoroughly investigate these bands with original digital Landsat data).

In analyzing the digitized image map data, it was observed that this band combination provided the best information available on vegetation. In fact, since the vegetation was most prominent within drainage channels in this desert area, these channels were better delineated. Additionally, surface textural changes were observed which had occurred either from local

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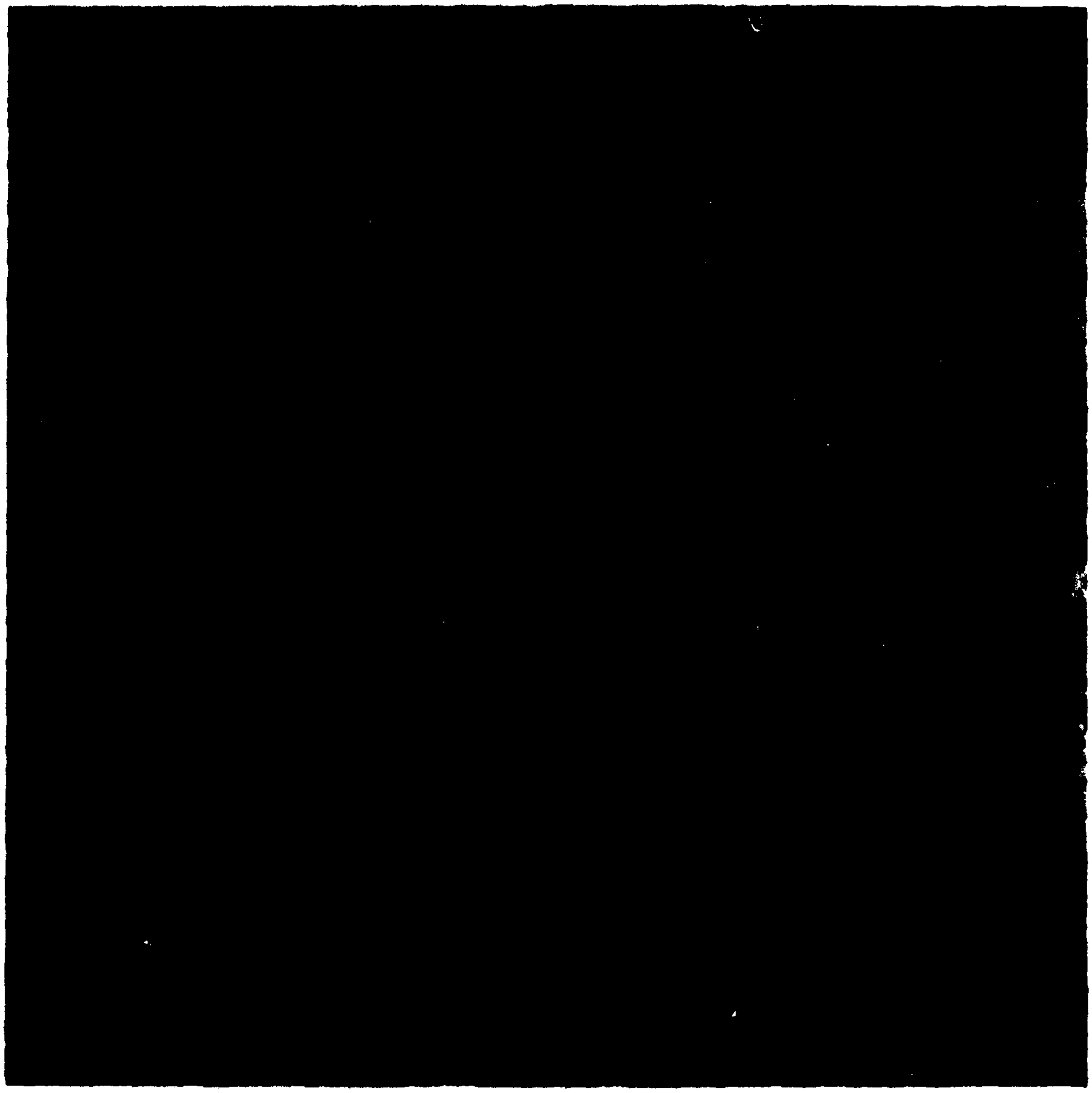
Illustration 20. Landsat TM Overview of NTS



water seepage at the bottom of alluvial fans or surrounding what appear to be large historical test sites. Some of these sites have now become repositories for hazardous wastes, and the prolific vegetation covering their surfaces and adjacent drainage channels is very evident. In reviewing the immediate target area enhanced through a linear stretch of four standard deviations, it was noted that despite the 30-meter spatial resolution, all the subsidence craters and most historical drill sites could be identified as well as the major roads within the area (see Illustrations 20 and 21). However, little new activity could be detected. The square test site just south of the largest subsidence crater, previously noted on the 1983 NHAP coverage, can still be observed although the easternmost half appears to be covered by growing vegetation -- an indication that the site is no longer active. Vegetation also appears to be growing in the bottom of the subsidence craters. In attempting to bring the digitized TM image to the same scale as the other images in Illustration 19, the scan lines with which the original TM image map was produced, show up as diagonal lines, creating noise that is distracting to the analysis. If the original digital TM data were available, this problem would not exist. Regardless of the noise problem, the ability to digitally overlay other data upon this image did contribute to the analysis and the amount of information extracted from the multisensor data sets.

Combining the PPDB image with the Landsat TM image produced a stereopair from data chronologically separated by seven years (see Illustration 22). The stereo view integrates the color data depicting vegetation information from the TM view with the higher spatial resolution data such as the target perimeter road from the PPDB product, providing an excellent means for visualizing the combined data from the two products. This capability also provides a simple and economical method for quickly detecting changes that have occurred in the interval between acquisitions. By simply flickering the data displayed in softcopy on the workstation or blinking one's eyes while viewing this stereopair on hardcopy, the new test site just south of the largest subsidence crater quickly becomes obvious from the 1984 Landsat image, whereas it doesn't exist on the higher spatial resolution PPDB data acquired in 1977, thereby dating the change as occurring between 1977 and 1984. Combining the Landsat TM with the 1983 NHAP coverage into a stereopair provides additional information as to when the change occurred (see

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Illustration 21. Topo/NHAP/TM/SEASAT Comparison

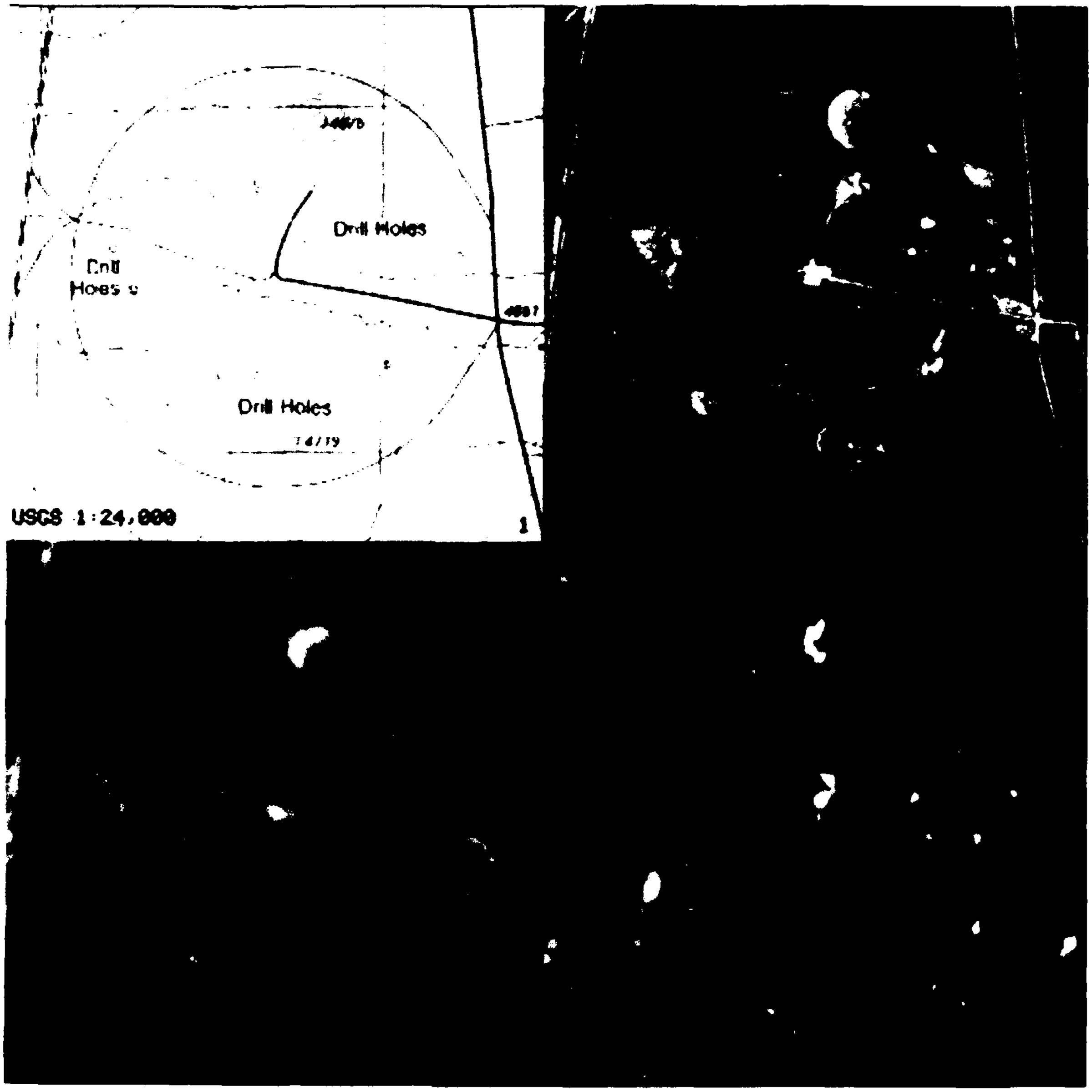

Illustration 22. Stereo of Landsat TM and PPDB

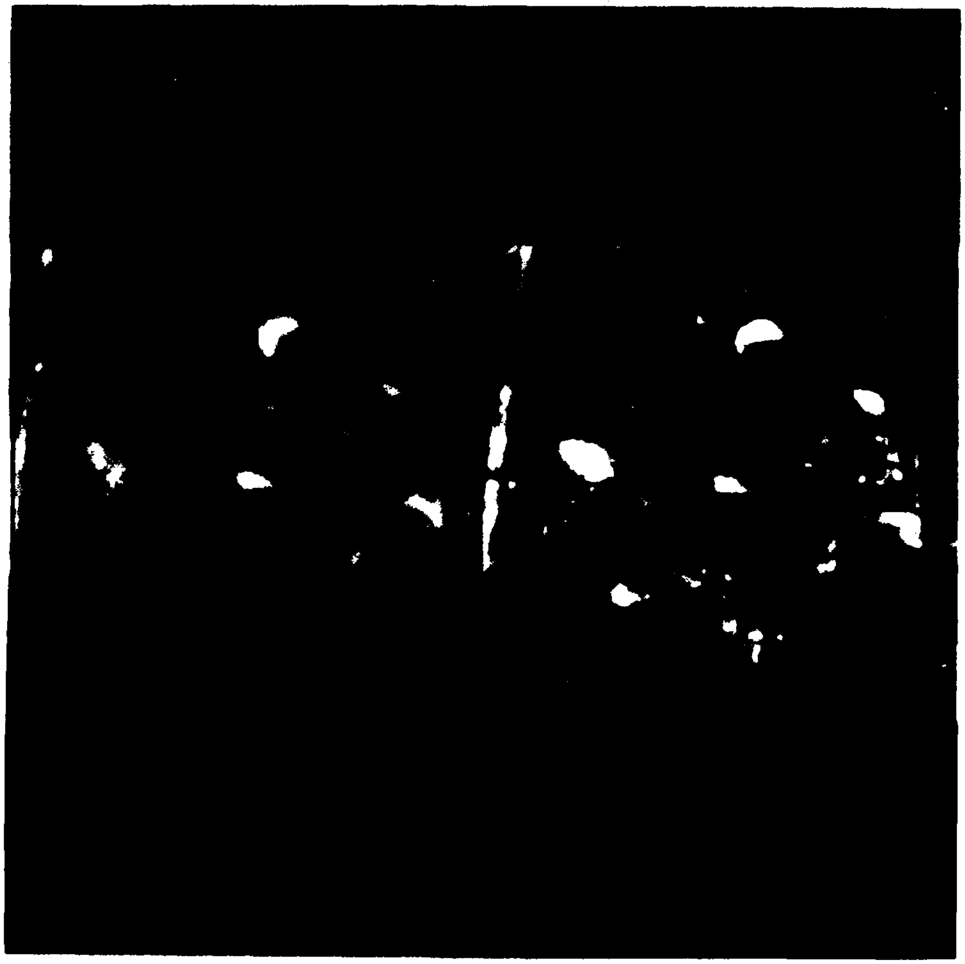

Illustration 23). Both the NHAP and Landsat images record the new test site, indicating that the site had been constructed prior to 1983. However, since a van can be detected on the NHAP imagery, the test for which the test site was probably built may be underway -- further delineating the timeline for the site's construction as being in the 1982/1983 time frame. Again, by visually combining this data into a stereo image, either on softcopy or hardcopy, the integration of unique data from each sensor allows more accurate and reliable analysis of the target site.

4.6.6 Thermal Imagery

One of the disappointments encountered during this study was the problem that no thermal imagery over the NTS could be located. Therefore, it was necessary to extrapolate information derived from another desert test site -- that of the White Sands Missile Range, New Mexico, where the DNA Misty Picture test was conducted in 1987. Referring back to Illustration 5 of this report, an observation can be made on how thermal imagery could be used to support test monitoring. All of the conventional digital image processing and superpositioning techniques described throughout this study could be used to fuse thermal data with other products. Thermal collections can be acquired day or night and through haze, but not through atmospheric or debris clouds. The most favorable time of collection is during the late evening hours or early morning prior to sunrise when the effects of solar heating are diminished and targets of interest identified. Under such conditions, relative thermal differences of one quarter degree centigrade can be observed. Correlating this data to absolute temperatures is dependent upon the thoroughness of atmospheric data collected during the thermal acquisition and presence of an absolute temperature control in the sensor and/or on the ground. Note that in previous Illustration 5, the bottom of the crater is hot (light colored) whereas the ejecta from the crater is much cooler (darker) than the solar-heated surrounding desert sands. This provides an excellent indicator that the detonation had occurred within a few hours prior to sensor acquisition. Note how accurately the extent and dispersal of the ejecta can be mapped. Such data provides clues concerning the shape of the explosive container and the size of the detonation. Other information that has been extracted from high spatial resolution thermal products are lightly-buried or

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Illustration 23. Stereo of NHAP and Landsat TM

surface-deployed cables; heat sources such as generators, vehicles, or thermal shadows (ghost images) of vehicles that have recently moved away; and venting from the test, etc. Functioning air conditioners within diagnostic vans or bunkers can also be detected by the presence of cool vents. Such information provides valuable data on the activity level of the test and supports predictions on test timelines. Because most of the unique thermal information on such tests is derived from the equipment being used, only high spatial resolutions on the order of five meters or better should be considered. Furthermore, because subtle relative thermal differences are significant, thermal collections through the 8-14 micrometer window are more useful than through the 3-5 micrometer window where the thermal signature must be more intense to be collected. Finally, if absolute temperatures are important, sophisticated means for recording atmospheric conditions, performing sensor calibration, and acquiring point ground inspection absolute temperature readings, at the time of acquisition must be considered.

4.6.7 Summary of Digital Imagery Analyses

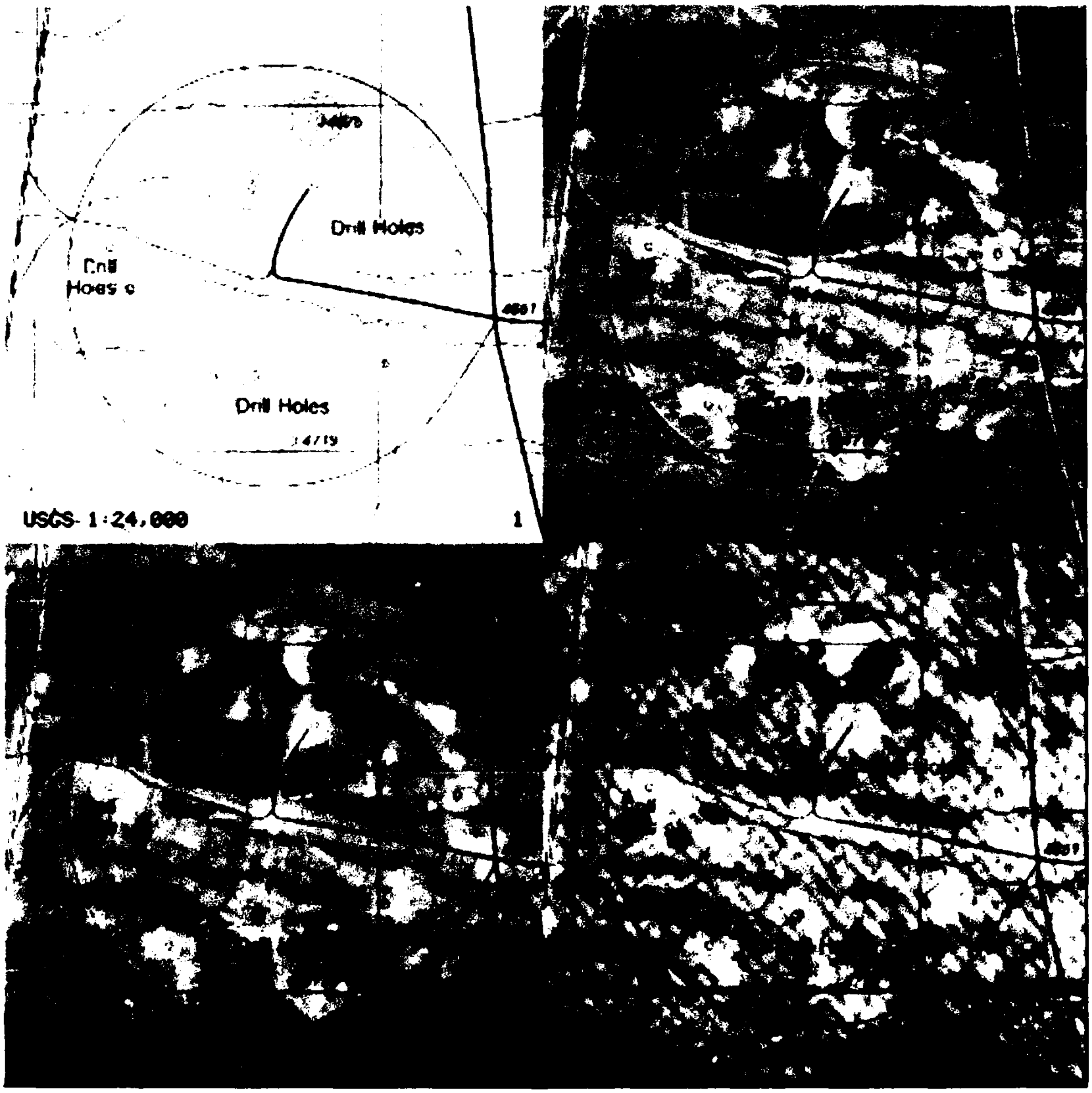
The products from five sensor collections over a target area within the NTS were analyzed to determine their utility for monitoring underground tests. Four of these imagery products had to be digitized since the original digital data was not available or because the original sensor product was photographic film. Multispectral, optical, and radar data of various spatial and spectral resolutions were reviewed independently, jointly, and in conjunction with such other digitized collateral data as geologic topographic maps.

Since no thermal data could be found over this specific site, extrapolations were made from thermal collections over historical simulated nuclear tests conducted by the DNA.

Study results indicate that each sensor collection added unique data to the analyses and would support the monitoring of known sites to ensure against covert testing and would aid in the investigation of test intents. The need for high spatial resolution collections was documented not only to identify test equipment results and such new natural effects as faults, landslides and spalling, but as a sharpening band to superimpose other imagery or data. Thermal data would support the identification of activity at sites by detecting such heat-inducing objects as generators, vehicles, etc., for identifying uncovered cables and equipment, and for documenting venting during a test. Finally, the relative thermal differences between rock types, vegetation, etc., would support monitoring post-event changes. However, spatial resolutions of five meters or better would be necessary to conduct these analyses. L-band radar data at 38-meter spatial resolution allowed for the detection of large terrain changes within a test area regardless of weather or time of day. However, much higher spatial resolutions will be necessary to identify test equipment or subtle changes in terrain. Thus, although new fault lines, landslides, spalling, etc., should be identified by radar, there is a need for spatial resolutions better than the 38-meter of SEASAT or the 5-meter data collected with military sensors over the DNA test. Furthermore, such higher resolution radar would allow for all-weather, day-night monitoring and change detection relating to covert preparation for tests where ground inspection is not present. Multispectral coverage at the Landsat 30-meter spatial resolution provides large, near-orthogonal overviews, additional data on vegetation, drainage, and on the delineation of landslide scars/talus. However, for more detailed analyses it too is limited by poor spatial resolution and relatively broad spectral bands.

The need to establish an accurate map-like data base of each suspect test site becomes apparent, and the greater the number of sensor products collected, the better is the chance for close monitoring. The techniques of digitizing all these products, regardless of their mode of documentation, has been proven effective. Current digitizing equipment is economical and can retain most of the spatial resolution now acquired from photographic products. The additional flexibility of reviewing several different images at similar scales either side by side, stereoscopically, or through three- or two-dimensional superpositioning, provides the imagery analyst with additional useful means to conduct his interpretation. Illustration 24 provides insight into the preciseness with which an analyst can scale and superimpose digitized data upon a variety of images. Through the use of these data, extrapolations can be conducted to support the development of a suite of sensors collecting at specific spatial resolutions

Illustration 24. Map Overlay on Imagery



and within specific spectral windows that would support test site monitoring. A workstation with a Geographic Information System (GIS) capability and peripherals for digitizing and hardcopy reproduction should then be considered for development. Phase II of this research will investigate both these areas.

4.7 PRECISE GENERATION AND SUPERPOSITIONING OF DATA FROM HARDCOPY

Most of the imagery available for this study is in the form of photographic film. Conventional photointerpretation of these products was conducted using a Richards HFO 4 Light Table Mensuration System (LTMS) equipped with a Bausch & Lomb Zoom 500 high magnification stereo microscope with a CRT display. The results of a comparative analysis of the data is represented in Illustration 25, which depicts the utility of each product for answering specific requirements. This information was compiled from analyses of both digital and hardcopy materials.

The primary difficulty in conducting these analyses was the need to either remember or produce transparent overlays which would outline the advantages of each product. Only two products could be viewed simultaneously and although much of the orientation and scaling problems could be compensated by the rhomboid lenses of the LTMS, inherent sensor distortions and the changing scales encountered on oblique images could not be completely counteracted. Further, means to produce overlays depicting changes are awkward and inaccurate. In order to investigate the utility of viewing such data without these distortions, and to determine the value of being able to store and map precisely the imagery and overlay-generated collateral information, the Autometric, Inc. Analytical Photogrammetric Processing System-IV (APPS-IV) was used. Although the math models for each stereo sensor was mandatory collateral, these were available in-house, as are numerous classified photogrammetric models. The APPS-IV was designed specifically for the generation of digital map-quality data from hardcopy stereoscopic imagery products. It has been used in the past to generate map-like products to support U.S. investigators in their INF treaty monitoring responsibilities. All stereo products were viewed on the APPS-IV where, through the use of sensor math models and supporting software, many of the inherent distortions

Illustration 25. Sensor Utility

MANMADE CHANGES

	New Roads	Drill Sites	Vehicular Tracks	Survey Activity	Spoil Piles	Test Equipment	Site Preparation	Security Measures	Open Storage	VIP Activity	No Activity	Abandonment
Landsat TM	X				X		X					
PPDB	X	X	X	?	X	?	X	X	X	X	X	X
NHAP BW	X	X	X	X	X	X	X	X	X	X	X	X
NHAP CIR	X	X	X	X	X	X	X	X	X	X	X	X
SEASAT	X						X					

NATURAL CHANGES

	Water Table	Vegetation	Microdrainage	Soil Texture	Soil Moisture	Desert Varnish	Microgeology	Ejection Craters	Subsidence Craters	Landslides	Spalling	Faulting	Soil Permeability
Landsat TM	X	X	X		X		?	X	X	X			?
PPDB	X			X				X	X	X		X	
NHAP BW	X		X	X				X	X	X		X	
NHAP CIR	X	X	X	X	X	?	X	X	X	X	?	X	X
SEASAT								X	X	X		?	

were obviated. Furthermore, three-dimensional fusing of two products from different sensors could be accomplished, as well as the accurate superimposing of imaged map data with the various images. Digitized data from one set of images can be generated, stored, and subsequently precisely superimposed in three dimensions over a stereo image from a different sensor. Updating the data by adding or subtracting information derived from more current image collections can be easily accomplished.

Although such analyses provided the analysts with a better means for viewing the data, it is debatable whether the time consumed in setting up the instruments and the cost of the equipment compensates for the added mensuration accuracies -- at the spatial resolutions of the products used in the analysis. Further, there is no practical way to produce hardcopy of the stereo image being viewed through the instrument optics. However, the ability to view large geographic areas in stereo is a definite plus compared to the small fields of view that can be displayed at maximum resolution in the digital arena. Additionally, height measurements of mapping accuracies which are routinely generated on the APPS-IV have yet to be demonstrated on low-to-medium-cost digital image workstations. Therefore, this system would answer the need to establish a reliable map base or GIS data of test sites to be monitored.

As an example, using the math model of the PPDB product in conjunction with the APPS-IV, several features of the target site were precisely mapped and the digitized data displayed on a Lexidata screen for analysis. The products were reviewed by the analysts, revised, edited, returned to the computer and subsequently plotted out in multiple colors using a Model Zeta 836 Nicolet Plotter (see Illustration 26). Note that terrain features, drainage patterns and manmade features can be accurately mapped, edited, the data scaled for superimposition over all the other hardcopy products, and viewed in three dimensions through the optics of the APPS-IV.

In summary, the use of sophisticated light tables such as the LTMS, provides additional support for superimposing two hardcopy images to either acquire three-dimensional data or for change detection -- without losses in spatial resolution encountered in the digitizing process. However,

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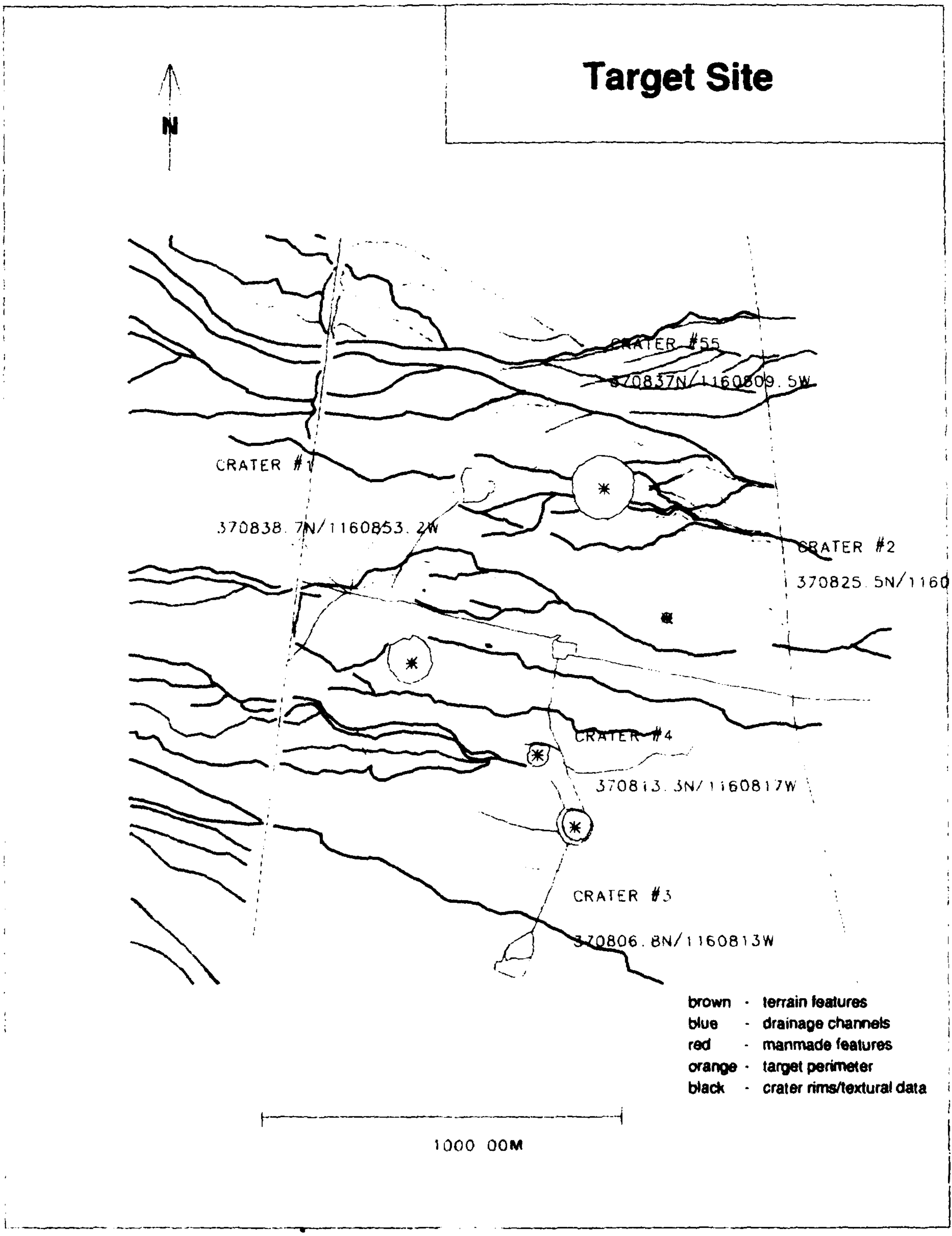
Illustration 26.



imagery distortion as those induced by the sensor itself or by varying obliquities, cannot be counteracted. Producing overlays to depict additional data or changes is cumbersome and inaccurate. Through the use of the APPS-IV, accurate feature mapping in three dimensions could be accomplished, viewed, edited and subsequently superimposed over other stereo products -- in three dimensions. Additionally, this was found to be the most accurate means for acquiring height information and establishing map accuracy data bases. The disadvantages of conducting analyses along these lines were the cost of the instrument, the time needed to set up precise models, the computer time, and the need to then integrate the hardcopy with the other digital imagery exploitation and processing techniques described in Section 4.6. As will be seen in Section 6.0, Autometric is developing a true softcopy three-dimensional stereo workstation capability (a softcopy APPS-IV) with all supporting sensor models and software as well as digital image processing and analysis means. This capability would be demonstrated and refined in Phase II of the SBIR.

SECTION 5 -- STUDY CONCLUSIONS

This study documents the first phase of a comprehensive investigation of available imaging sensor products and the means to integrate them to support requirements for monitoring underground nuclear tests. The concept of precisely merging unique information derived from each sensor by digitizing the hardcopy product and combining pertinent data with softcopy collections, as well as digitized collateral data, shows excellent potential. Since a plethora of imaging products can now be acquired (and more are coming), the data from the five missions that were used in this analysis are only representative of the sensor capabilities that can be used today or in the near future. It becomes immediately apparent that high spatial resolution imaging systems will play an important role in monitoring the subtle changes that occur in the preparation, testing and post-detonation at nuclear facilities. However, in the search for new test facilities, and in the periodic monitoring of test preparations and changes throughout large test ranges, sensors that provide large area coverage are also a necessity. This requirement does not demand the very high spatial resolutions needed to analyze tests but such products will provide excellent map-like data bases upon which to display or embed data from the high resolution sensors and/or ground inspection data.

The following specific conclusions can be made concerning the results of this investigation.[4] They provide points of reference from which extrapolations can be made for additional RDT&E which must be accomplished before accurate monitoring of underground tests can be realized.

- The identification and monitoring of foreign nuclear test sites will continue to be an important military/intelligence requirement whether within an arms control/verification agreement political climate or a more hostile and confrontational environment.

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[4] A separate set of conclusions are contained in a classified Appendix A (under separate cover).

- The surface effects from simulated aboveground and operational underground nuclear testing are well documented and can be differentiated through the use of current civil-commercial imagery sensor products.

- All nuclear tests demand months of preparation prior to detonation. Important keys to new activity at known sites can be detected with current civil-commercial imaging sensors as soon as ground scarring from vehicular traffic and earth moving for site preparation begins.

- Predictions on the status of a test can be produced by the analysis of visual keys that have been documented from other tests.

- An invaluable means for monitoring underground tests is to establish a comprehensive multisensor, multispectral data base of known test sites and to update the information on a periodic basis. This assumes greater importance if a universal open-skies policy is adapted. Such a data base can greatly aid ground inspectors and analysts by the merging and fusion of ground data into the overhead sensor base.[5]

- Radar imagery from the 1978 SEASAT mission can identify the difference between large subsidence and ejecta craters and can detect earth scars that denote new activity. However, the 38-meter spatial resolution would not allow the detection of most new fault lines that may be produced by underground nuclear tests.

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[5] Imagery exploitation work by Autometric, Inc. has proven the importance of the use of overhead imagery combined with ground inspection data in support of the INF Treaty. These efforts used the APPS-IV with Super-P™, VAX-750, Zeta plotter, and associated software similar to that investigated in this Phase I SBIR.

- The primary advantage of radar at SEASAT spatial resolutions is for detecting initial scarring at known test sites where atmospheric or ambient light conditions may limit photographic or electro-optical collections. Higher resolution SAR would allow for all-weather, day-night monitoring of covert preparations, conduct, and post-test changes.

- Thermal collections at the 120-meter spatial resolution of the Landsat sensor appears of little use for monitoring tests. However, if thermal collections were available that could acquire spatial resolutions of five meters or better and thermal resolutions to a quarter of a degree centigrade, day and night fair weather activity monitoring of above-surface test equipment could be beneficially conducted.

- High spatial resolution black and white film products provide excellent means for fair weather daytime monitoring of known test sites. At spatial resolutions better than a meter, test equipment and drilling sites can be identified, as well as post-detonation changes in terrain or test facilities.

- High spatial resolution (better than three meters) color infrared film products provide additional data about surrounding vegetation and changes in water table or surface textures that affect growing vegetation. Such sensing also detects moisture changes in dry soil that may be due to water table changes.

- Landsat 30-meter Thematic Mapper multispectral data provides a near-orthogonal, planimetric, large area data base upon which to precisely superimpose collateral data acquired from maps, high spatial resolution sensor products, or other collateral graphic or point source (ground) data. This multispectral collection capability provides information on vegetation and geology that cannot be acquired by other single-broad-band sensors. Higher resolution SPOT and/or aircraft multispectral/hyperspectral imagery would provide additional technical information but remains to be investigated.

- Digitizing photographic materials and displaying the data on a digital processing workstation induces a slight loss in spatial resolution when compared to the original or second-generation transparency. The extent of the loss is dependent upon the initial image quality, the spot size used for digitization, and the quality of the display screen. For most conventional products and all graphical data, such as maps, a 300-dots-per-inch digital scanner provides adequate products.

- The 3M prototype Color Laser Image (CLI) provides valuable and useful color hardcopy imagery direct from the digital image processing workstation with all enhancements and superimposed graphical data.

- The flexibility for digitally enhancing and/or precisely superpositioning data from two or more sensors, one upon the other, more than makes up for the loss of spatial resolution due to the digitization and display process.

- Digitized stereo images derived from adjacent pairs from the same sensor, from different missions using the same sensor, or from different missions using imagery from different sensors, provide excellent means to detect changes.

- The depth/height information derived from digitized stereo products produced from two different sensors cannot presently be accurately reduced to absolute height figures but can be digitally derived using a digital analytical stereoplotter using same sensor stereo imagery.

- The use of an APPS-IV to collect accurately digitized three-dimensional photogrammetric data, provides excellent map-like bases to support site monitoring and for precise updating of other collateral information.

- The APPS-IV and similar hardcopy devices are presently the most accurate means for acquiring accurate height measurements but digital stereoplotters have been developed which will be benchmarked against the hardcopy plotters (see Section 6).

SECTION 6 -- RECOMMENDATIONS FOR PHASE II AND POTENTIAL PHASE III COMMERCIAL SPIN-OFFS

6.1 PHASE II RECOMMENDATIONS

The following preliminary Phase II SBIR recommendations are made. These suggestions, as well as other recommendations and proposed work, will be presented in Autometric's formal Phase II SBIR proposal.

Under Phase II, Autometric plans to pursue two separate tasks in parallel. Task 1 will be to participate in an actual underground test at the NTS by scheduling multiple sensor aircraft for collections as well as the tasking of civil and national satellites to acquire imagery before, during, and after the test detonation. All products will then be analyzed using the latest hardcopy and digital analysis techniques. The intent will be to isolate the characteristics of a suite of sensors that should be used to answer test monitoring requirements and to document gaps in the spectrum that need to be filled to support verification of underground nuclear tests.

Task 2 will be to design and develop a dedicated prototype workstation that will contain all the peripherals needed to economically digitize, store, process in softcopy, and reproduce in hardcopy all the data from multiple classified and unclassified imaging system products to support treaty monitoring. Following are the areas that should be investigated under Phase II of this project.

6.1.1 Task 1 -- Participate in Department of Energy (DOE) Underground Test and Analysis

1) Determine the DOE schedule for future tests at the NTS and work with them to acquire seasonal coverage before, during, and after the test.

2) Select, from available imagery collection platforms, those that have potential for acquiring data that will document the

key information stipulated in Phase I, and schedule specific acquisitions.

3) Acquire original sensor products from both classified and unclassified sensors (original negative/positive from film-return sensors and digital tapes from digital-return systems).

4) Schedule aircraft overflights using such multispectral sensors as the NASA AVIRIS (220 spectral bands) or the MTL Corporation 63-spectral-band sensor.

5) Determine the utility of subpixel analyses to detect spectral data from within a pixel from multispectral sensor products for underground testing and implement in Task 2, as appropriate.

6) Refine the most promising digital image processing techniques investigated under Phase I accenting new sensor products and the latest image exploitation equipment.

7) Study and document the spatial resolution tolerances and economies of a 300 DPI scanner, a scanning microdensitometer and the WJSA stair-step digitizer, for digitizing imagery and collateral data.

8) Investigate additional means to acquire high quality color reproductions of digital products, including the modified 3M prototype Color Laser Imager that will be brought on-line at Autometric in the late summer of 1990.

6.1.2 Task 2 -- Develop Prototype Workstation

1) Establish a complete softcopy stereoscopic image processing workstation testbed in Autometric's tempested image exploitation laboratory at its Headquarters building in Alexandria.

2) Benchmark and evaluate the capabilities of the softcopy workstation versus the APPS-IV for the related tasks conducted in Phase I of the SBIR.

3) Expand the capabilities and use of the digital workstation to include: variable flicker for three-dimensional registration/superpositioning; color graphic overlays of collateral/ground acquired data; acquisition of thermal IR imagery and a thorough evaluation of its capabilities singularly or in combination with other sensors; fusion of higher resolution SAR with optical/electro-optical imagery; and on-line interface of the input digitizer and color laser imagery output device with the softcopy workstation to establish an end-to-end system.

4) In conjunction with Task 1, acquire necessary overhead imagery and collateral data for test and evaluation of underground test detection/verification of U.S. and foreign sites, including: Landsat TM, SPOT, aircraft multispectral/hyperspectral data, other aircraft multisensor imagery, handheld shuttle optical camera imagery, other NASA experimental sensor imagery, and classified imagery.

5) Incorporate Geographic Information System (GIS) software into the workstation to provide automated geographic, timeline, environmental, and other expert system parameter-potential capabilities for the workstation.

6) Using the workstation testbed, develop matrices of capabilities for the various sensors, both single sensor and integrated multisensors. These quantitative matrices will be based on human factor testing and provide statistical summaries of results of speed, accuracy, and completeness of extracted information concerning underground test detection, identification, and activity/status determination.

6.2 POTENTIAL PHASE III SPIN-OFFS

Phase III would establish for the military, intelligence, and arms control communities, the imaging sensor suite for monitoring underground nuclear tests, document the analytical tools to be used, and develop a dedicated workstation that would accomplish monitoring requirements.

The potential commercial spin-offs of the work conducted on the SBIR primarily involve what is called "value-added" remote sensor image processing and exploitation. This would include the use of advanced hardware, software, and techniques/methodology which have important commercial ramifications. Value-added, user-oriented exploitation is one area where U.S. commercial companies, especially small businesses, still have a lead over foreign competition. Furthermore, such value-added applications are the key to the remote sensing market since it is only when useful information is provided to the customer/user that a remote sensing imaging system fulfills its purpose. The RDT&E conducted on this SBIR, by treating the fusion and integration of multiple sensor imagery and other collateral data, is thus at the cutting edge of technology for meeting additional commercial uses. A few of these uses include:

1) Medical applications -- early detection of tumors, body scanning/imaging, two-dimensional/three-dimensional processing of thermographic imagery, magnetic resonance imagery (MRI), X-rays/radiology, AIDS/viral microscopy of cultures, etc.

2) Environmental use of imagery processing output products for legal defense of a company's pollution activities.

3) Insurance company use of imagery processing output products for disaster inventory.

4) Media use of imagery processing output products for TV newscasting, documentaries, etc.

5) Overhead and ground sensor exploitation for industrial and commercial siting of plants, facilities, transportation planning.

6) Counternarcotics interdiction and also as evidence for criminal investigations for drug and other crimes.

7) Various commercial value-added services, government program support (Federal-NASA, DoD, Interior, EPA, etc.), international (arms control, Aid/World Bank, foreign governments, etc.), and State/local (environmental, planning, taxing, etc.).