

AN ASSESSMENT OF ALTERNATIVE SAR DISPLAY FORMATS: ORIENTATION AND SITUATIONAL AWARENESS

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Abstract - This study explores the operational utility of fusing synthetic aperture radar (SAR) imagery and digital terrain map (DTM) data. Specifically, the two-dimensional (2D) display of SAR imagery was compared against a two and a half dimension (2 1/2D) display of SAR overlaid on corresponding DTM data. Eight imagery analysts (IAs), assigned to the Israeli Ground Corps Command Imagery Analysis Unit and to the Israeli Air Force, and two weapon system officers served as subject matter experts. The measures employed in this comparison included both an assessment of operator situational awareness (SA) and of performance in an information extraction task. Based on the SAR imagery which was used in the experiment, performance measures (accuracy and speed in feature location) and SA measures did not yield significant performance differences between the 2D and the 2 1/2D displays. The average time required to complete each task was significantly longer for the 2 1/2D displays. Based on experience, the SME's opinion was that the 2 1/2D imagery display may be potentially helpful in the performance of various imagery analysis tasks and in enhancing SA.

Key Words: Synthetic Aperture Radar (SAR), Digital Terrain Map/Elevation Data, Imagery Exploitation, Situational Awareness, Information Fusion.

1. Introduction

1.1 Background

Synthetic aperture radar (SAR) sensors offer two compelling advantages over conventional (electro-optical) sensing technologies: stand-off range and adverse weather capabilities. SAR images can be formed with effectively no loss in resolution out to the limits of the system's stabilization and motion compensation capabilities. SAR sensors can "see" through clouds and through light rain. Further, depending on their coverage mode and data processing limitations, SAR sensors can be capable of high area coverage rates. These attributes make SAR imaging a valuable resource for tactical and theater airborne reconnaissance, surveillance and target acquisition applications.

The air forces of both the United States and of the State of Israel have great interest in exploiting these

capabilities. The United States Air Force has operational SAR capabilities in the B-1B, F-15E, J-STARS, and U-2 systems and plans to include SAR as a primary imaging mode in the Global Hawk uninhabited air vehicle. The Israel Air Force has operational SAR capabilities in their Phantom 2000 and F-15I multi-role aircraft and has other SAR capabilities in development. (A prior study [1] explored the benefits of SAR display enhancement algorithms in an image interpretability task.)

SAR, however, is a non-literal imaging sensor. That is, the imagery produced by a SAR does not resemble a photograph taken of the same scene. The intensity values in the SAR image are proportional to the radar cross sections of the corresponding points in the ground scene (and not to their visible wavelength reflectance). The impulse response function of the SAR (the fundamental determinant of system resolution) includes side lobes. Thus, the return from a point on the ground may include energy contributed by adjacent scatterers. The "shadows" in a SAR image are caused by the active illumination of the scene by the emitting radar (and not by the sun angle). The perspective of a SAR image is that of an observer looking down on to the scene from directly above, while it is being illuminated by the radar from one side (the location of the SAR).

Because of the non-literal nature of the SAR image, operational questions exist regarding how well an imagery analyst (IA) can orient it against a map reference. A fundamental imagery exploitation task is to confirm (or plot) the actual ground coverage of a collected image against a map reference. (A recent survey of IA tasks and workstation functional requirements is presented in [2].) Several other standard imagery exploitation tasks (e. g., landform analysis, traversability studies) require that the operator interpret the image so as to assess the basic geologic and terrain characteristics, including judgments of the heights of terrain features and the grades of slopes. Further, orientation may require the IA to locate salient terrain features and to match them against their map references. Understanding of the terrain contributes significantly to the establishment and maintenance of situational awareness (SA), affording the context within which other imagery interpretations may be made. The human operator is unique in having the ability to apply contextual

information to the interpretation of complex visual stimuli (such as reconnaissance imagery).

Endsley [3] has been a primary researcher in studying situational awareness. This study attempts to extend her model (Figure 1) to the intelligence exploitation domain. Within the definitions implicit in her model, the SA metrics employed correspond to Level 1 SA.

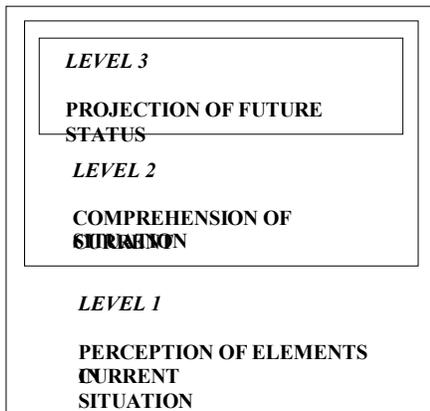


Figure 1. Model of Situational Awareness (from Endsley, 1994)

SAR is not the only technology which may support these operational requirements. Digital terrain map (DTM) data, consisting of elevation “posts,” equally spaced in latitude and longitude, provide another source of information regarding the heights and slopes of the terrain. DTM data can be viewed in two dimensions (2D), as elevation contours, or as a continuous depiction in which elevation is coded by luminance values or colors. 2D image formats may be rotated so that North (or any arbitrary direction) is toward the top of the display. Alternatively, DTM data may be displayed in 2_D in which a 3D “model” of the terrain, with a shading scheme applied as if it were illuminated by the sun, is projected on to the 2D display surface. 2_D DTM displays may be rotated in both azimuth and elevation to change the effective viewpoint of the observer.

Fusion also offers potential capabilities to support enhanced orientation, situational awareness, and information extraction capabilities. Disparate data sources, such as SAR imagery and DTM elevations, may be combined (overlaid) so as to support a 2_D display of the SAR images. Figure 2 [4] depicts the model of the levels of fusion adopted by the US. The fusion of SAR and DTM, as in this study, correspond to Level 1 in this model.

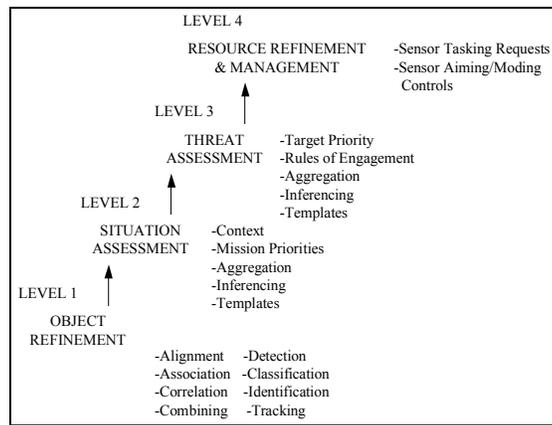


Figure 2. Model of Data Fusion

1.2 Objective and Approach

The objective of this study was to perform an operational assessment of the relative utility of 2D and 2_D displays of SAR imagery. In the 2D case, the SAR images were viewed conventionally. In the 2_D case, the SAR image was overlaid on the corresponding DTM model. Subject matter experts (SMEs), primarily military IAs assigned to the Israel Air Force (IAF), the Intelligence Command, or the Ground Corps Command, performed orientation and information extraction tasks using both display formats. The study was conducted at the facilities of Synergy Integration Ltd., Tel Aviv, with the support of PAMAM Human Factors Engineering Ltd., during the period 19 August through 17 September 1998.

2. Method

2.1 Imagery

The SAR imagery used in this experiment was acquired by a developmental sensor flown on the Israel Aircraft Industry’s Boeing 737 multi-mode radar testbed aircraft. The imagery had a nominal resolution of 1.2 m. The imagery, in detected form, had a nominal dynamic range of 8 bits (or 256 gray levels). All imagery was acquired at high grazing angles (approximately 45 degrees).

Three swaths were provided by the Israeli Ministry of Defense. The first included coverage of the Armored Command Museum at Latrun. The second included the area of Rosh Ha’ayin and the third included coverage of Ben Gurion International Airport. Thirty-eight stimulus images were extracted from the Latrun and Rosh Ha’ayin swaths. Six images, used only for

familiarization with the task and practice with the apparatus, were extracted from the Ben Gurion coverage.

The Rosh Ha'ayin and the Latrun swaths differed in scale. In the Rosh Ha'ayin swath each centimeter of the image represented approximately 60 meters on the ground. In the Latrun swath each centimeter of the image represented approximately 92 meters on the ground. As a result the width of Rosh Ha'ayin swath was approximately 1 km by 1 km and of the Latrun swath approximately 1.5 km by 1.5 km. The resolution of each of the images was 700 by 700 pixels.

2.2 Selection of "Targets"

The experimental design was constrained, to some extent, by the coverage of the available imagery. Since the objective of the experiment was to investigate the effect of SAR imagery overlaid on a three-dimensional terrain elevation database and viewed in a 2_D display on both orientation and situational awareness, no buildings were included. A senior and highly experienced IAF IA first determined the coverage of the SAR imagery against a 1:50,000 scale survey map. Features (such as river bends, confluences/divergences of streams, the intersections of dirt roads, etc.) were selected from the map information for use as designation "targets" and their Universal Transverse Mercator (UTM) coordinates were read and recorded. These same features were then located within the SAR images and the corresponding pixel location was read and recorded. This process was repeated until all 38 stimulus targets and the six practice targets had been selected. The target location coordinates were maintained as the "school solution" for scoring the accuracy of the designation portion of the task. The imagery was then divided into 22 matched pairs (one half of each pair to be presented in 2_D and the other half in 2D.) The pairings were made on the basis of containing similar targets within similar backgrounds.

2.3 Overlay of SAR Imagery onto DTM Data

Commercial, off-the-shelf software (MultiGen II Pro, from MultiGen Inc., San Jose, California) was used to convert the SAR pixel coordinates into UTM coordinates, the reference system used for the DTM data. Multiple control points were selected from each of the SAR images and their geographic reference locations were carefully determined from the map. A transformation program, using these control points,

was used to convert every pixel location into its corresponding UTM coordinates. One SAR image from each matched pairing was then overlaid onto the corresponding DTM elevation data (using the same software package). The product of this procedure was a 2_D representation of the area (as compared to the 2D representation of the original SAR imagery).

No additional exaggeration to the elevation data was introduced. Thus, the displayed image of the overlaid SAR and DTM depicted ground distances (x and y) and heights (z) in the ratios of 1:1:1.

2.4 Apparatus

The images were displayed and designation coordinates and response times were recorded using a Silicon Graphics Incorporated (SGI) ONYX graphics workstation equipped with an Infinite Reality Engine multi-processor. The workstation was also equipped with a SGI model CM2187ME 533 mm (21 inch) diagonal color monitor. The display resolution (full screen) was 1280 by 1024 pixels. The brightness and contrast controls of the display were set by the Experimenter. The apparatus was located in a laboratory setting and was used to support both stimulus preparation and data collection. All stimulus imagery was displayed using commercial, off-the-shelf software (the VEGA general visualization environment from Paradigm Simulations Inc., Dallas, Texas). The displayed image (700 by 700 pixels) was approximately 200 by 200 mm (8 by 8 inches) on the monitor.

2.5 Subject Matter Experts

Five enlisted IAs from the Israel Defense Force Ground Corps Command's Imagery Analysis Unit, three IAs from the IAF, and two Weapon System Officers (WSOs) of the IAF, served as subject matter experts (SMEs). All were male. They ranged in age from 19 to 25 years. Their experience in tactical imagery exploitation ranged between six months and 6 years. Four of the IAs and both WSOs had some SAR imagery experience; all of them had experience in the exploitation of electro-optical (photography and television) sensor collections and all had previous experience in performing softcopy imagery exploitation. None of the SMEs had had previous experience in exploiting high resolution SAR imagery (as was used in the present study). All SMEs had 6/6 (20/20) vision, uncorrected or corrected, and all had received formal military training in imagery analysis during a three month duration Service school.

2.5 The SME Task

Figure 3 depicts the sequence of events which composed the experimental task. Upon arrival at the laboratory facility, the SMEs were informed as to the purpose of the study and instructed regarding the conduct of the experiment. The instructions to the SMEs explicitly placed primary emphasis on the accurate performance of the designation component of the task but also emphasized the requirement to complete the task as rapidly as possible. The instructions also included the caution that the imagery was more recent than the map and might contain (extensive) differences with respect to the addition of man-made structures such as buildings and roads.

Information regarding the SME's background, training and imagery exploitation experience was elicited through a brief questionnaire which included questions regarding their training and experience in the exploitation of SAR imagery and their experience in interpreting softcopy imagery. The SME was then seated at the graphics workstation.

At the beginning of the task, each SME was shown an extract from a 1:50,000 scale, color, topographic Survey Map of Israel. The map, oriented north-up and covered approximately 2 km by 2 km in area, had been annotated to depict the coverage of a SAR image at a different orientation and included a red dot marking the location of a target. This map allowed the SME to understand the relative differences in coverage between succeeding map extracts and their corresponding SAR images. They were then instructed in the use of the apparatus for the imagery orientation and target designation portions of the task. The practice images were used to allow the SMEs to gain proficiency in the use of the equipment, the orientation and target designation components of the experimental task, and the nature of the SA questions. Any remaining questions that the SMEs might have regarding the task were answered by the Experimenter at this time. When the SMEs reported that they were confident in the execution of the task, the data collection trials were initiated.

At the beginning of each of the 38 data collection trials, a 1:1 scale extract from a 1:50,000 scale, color topographic Survey Map of Israel was provided to the SME. The map extract was always oriented North-up and covered approximately 2 km by 2 km in area. The header on the map copy described the type of target to be located (e. g., dome, intersection of a dirt road and a stream, etc.) while the exact location of the specific

target of interest was depicted on the map itself by a small red dot. The map extracts were mounted as successive pages in a flip chart-type booklet. The Experimenter initiated each trial (by depressing a specific function key on the keyboard). The SME was permitted 15 seconds for map study. During this interval, the image display region was blank (showing a solid, medium luminance, light blue field). The Experimenter informed the SME whether the current trial was a 2D or 2_{1/2}D display format. The SAR image, containing the target, then appeared on the workstation display. The images were always presented so that the radar shadows pointed toward the bottom of the display (i. e., as if the radar were illuminating the ground from along the top edge of the display). No restriction was placed on the viewing distance between the SME and the workstation monitor.

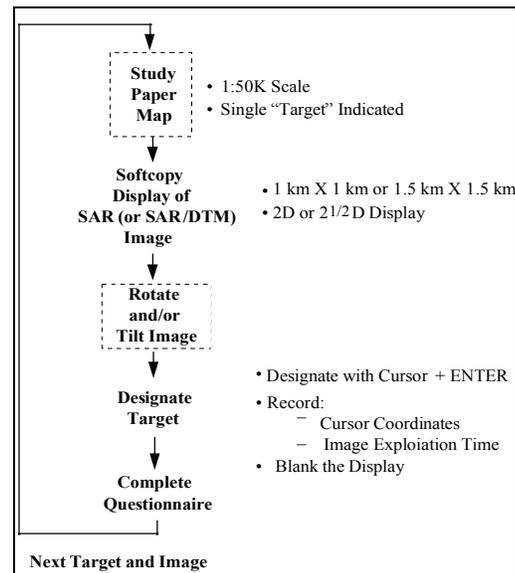


Figure 3. Flow Diagram of the SME's Task

The SMEs were permitted up to three minutes (180 seconds) during which they were required to orient themselves to the SAR image in the context provided by the map information (which was available throughout the trial), to locate the pre-briefed target, and to designate the target. At the completion of the tasks the display automatically went blank and performance time was recorded. If the SME did not respond within 180 seconds the display went blank and the trial was recorded as having "timed out". During this three minute period, the SMEs could use the left and right arrow keys on the workstation keyboard to rotate the image through a full 360 degrees of azimuth. The up and down arrow keys "tipped" the image through 90 degrees of "elevation."

Rotation in both azimuth and elevation were continuous and could be applied in any combination.

For each SME, half the stimulus images were presented in overlay on the DTM elevation data. In these cases, rotation of the displayed image produced a 2_D view. In the other half of the trials, a 2D view was presented, the arrow keys could still be used for tip and rotation but no elevation data were overlaid on the SAR images. The mouse was used to drive an “arrow” cursor on the display to point on the image. When the SME had located the target, the ENTER key on the keyboard was used to record the target location into the data file for that trial. (The keyboard ENTER key was preferred to the mouse buttons in order to prevent involuntary motion of the mouse cursor during designation).

Upon designation, the display was blanked and the location of the designated point was automatically recorded, along with the time between stimulus onset and the act of target designation. The SME then flipped the page in the map booklet (thus precluding any further reference to the map) and found two questions regarding the image presented during the just-completed trial. These SA questions dealt with absolute or relative terrain height judgments or with the relative location of other objects in the SAR image. The answers to the questions were recorded manually by the Experimenter. (This allowed for immediate answers to any SME requests for clarification of the SA questions.)

2.6 SA Questions

Two SA-related questions were developed by the Experimenters for each target image. The questions dealt with absolute or relative terrain height judgments (e.g., which bank of a stream was higher?, which slope of a dome was steepest?) with the direction of objects (e.g., what was the direction of the stream?) or with the relative location of objects in the SAR image (e.g., in which direction from stream bend were two large buildings?). The SA questions were presented in multiple choice form, three possible answers to each question were presented and the SME had to select the correct one. No time limit was imposed in answering these questions.

Once the SA questions had been answered, the trial was completed. The SME then indicated readiness to proceed with the next trial. This sequence was repeated until all 38 images had been presented to the SME. The SMEs were given a short break after each

group of eight to 12 trials (while the Experimenter loaded a different SAR swath).

2.7 Rating Scale Questions

After all 38 stimulus images had been presented, the SME was asked to complete a series of rating scale questions regarding overall impressions of the task and of the two different display formats. Each scale consisted of seven points with semantic anchors at each endpoint (as shown in Figure 4).

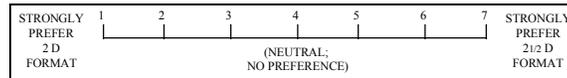


Figure 4. Rating Scale with Semantic Anchors

A rating of one always meant that the 2_D display greatly degraded the SME’s ability to perform the referenced function while a rating of seven always meant that the 2_D display greatly enhanced that ability. The first group of questions dealt with comparisons between the 2D and 2_D display formats with respect to: performing general orientation, assessing the structure of the terrain, assessing differences in terrain heights, and assessing terrain slopes. The next scale required the SME to rate utility of the 2_D display format in supporting general imagery interpretation tasks. Another set of questions related to SA. The SME was asked about the differences between the 2D and 2_D display formats in supporting giving answers to the SA questions. The SMEs were also asked to comment on whether they relied primarily on the map extract or on the SAR imagery in answering these questions. They were also requested to comment on the relevance of the SA questions to their current military duties. Provision was also made for the SMEs to record any overall impressions or comments regarding the entire experiment

Upon completion of the rating scales, data collection was ended and the SME was thanked for participation in the experiment. Each SME participated for approximately two hours, including instruction, practice, data collection, and completion of the questionnaire.

2.8 Experimental Design

A mixed, within-subject experimental design was employed. Half of the SMEs were presented with one half of the matched SAR image pairs overlaid on to

the DTM data; the other half of the SMEs were presented with the alternate half of the image pair presented in non-overlaid format. Half of the SMEs were presented with the experimental imagery in the reverse order from that presented to the other SMEs. This counterbalance was to protect against learning effects. Thus, there were four unique combinations of imagery presentation: order of presentation and DTM or non-DTM underlay (the independent variable of interest).

3. Results

3.1 Designation Accuracy

Accuracy of the terrain feature designations was measured in cm on the displayed image. The mean accuracy score for the 2D display was 1.33 and for the 2_D display 1.39. This difference is not significant.

3.2 Response Time

Designation time tended to be longer for overlaid SAR-DTM images. The average response time for the 2D images was 51.9 seconds and for the 2_D 60.6 seconds. This difference is statistically significant ($p=0.001$). Designation times for the Latrun swath (51.79 seconds) were significantly shorter than for the Rosh Ha'ayin swath (60.68 seconds) ($p=0.001$). (The shorter response times for the Latrun swath may be due to the higher availability of salient human-made features in the images of the Latrun area.)

3.3 SA

Each trial was followed by two SA questions. A score of 1 was assigned to each correct answer and 0 to wrong answers. SA scores were computed for trials with correct and partially correct target designations only. The final SA scores were computed as the sum of points for each trial. The mean SA scores for the 2D images was 1.08 and for the 2_D images 1.04. This difference is not significant.

3.4 Rating Scales Responses

The first four questions on the rating scale dealt with the strength of the SMEs preference for either the 2_D or the 2D SAR display format in the context of supporting the IA's ability to orient to the terrain scene. The first scale addressed general

orientation, the second addressed the assessment of landforms/terrain structure, the third understanding of terrain height differences, while the fourth explored understanding of differences in terrain slopes. As depicted in Figure 3, the SMEs, as a group expressed a marked preference for the 2_D display format. (In the Figure 5, a mean rating of 4.00 reflects no preference between the two formats.)

The fifth rating scale required the SMEs to express their preference in the context of the utility of the display format to support imagery interpretation in general. A preference for the 2_D format was found.

The sixth rating scale explored the two display formats in the context of SA. Again, a preference for the 2_D was elicited.

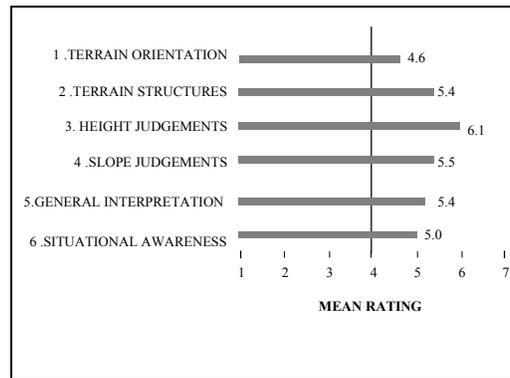


Figure 5: Mean Ratings.

All ratings were significantly higher than the neutral score (4.0). Table 1 presents the statistical summary for 10 SMEs.

Table 1: Mean ratings and T scores for the six rating scale questions:

Question	Mean Rating	T score	Probability
1	4.6	2.64	0.05
2	5.4	4.24	0.01
3	6.1	13.74	0.001
4	5.5	3.53	0.01
5	5.4	5.22	0.001
6	5.0	2.55	0.05

3.5 Observations

Before discussing the implications of the results from the formal measures used in the study, some

observations on the part of the Experimenters, made during the data collection runs, may give the reader insight into the study.

None of the SMEs had any apparent difficulty in employing the display/controls mechanization (arrow keys, mouse, enter key) used in this study.

Although none of the SMEs had any experience in the exploitation of high resolution SAR, they were all able to complete the target designation task without any reported difficulty.

All IAs had received training in landform and traversability analysis as part of their IA school curriculum.

Some SMEs indicated that the effective usage of 2_D images may require experience and perhaps even formal training.

Wide-ranging, individual differences were observed with regard to the strategies employed by the SMEs in viewing the SAR display. Some SMEs physically rotated the paper map to match the orientation of the SAR (regardless of whether DTM data were available). This kept the radar shadows pointing toward the bottom of the display – a technique that IAs are taught to employ to avoid a “false” reversal in apparent elevation / depression of the scene. Others appeared to first rotate the SAR display (again regardless of the format) and then to quickly tilt the displayed image, apparently to gain an appreciation for terrain relief.

4. Conclusions and Recommendations

4.1 Conclusions

High resolution SAR imagery, collected at high grazing angles, does not appear to present any of the difficulties conventionally associated with low and medium resolution non-literal imagery at least in the context of the present salient landform designation and terrain-based SA tasks. This also suggests that only minimal impact to the training support system may be encountered as these systems become operational.

Designation scores with the overlaid SAR-DTM imagery (2_D) produced slightly higher accuracy scores than SAR alone (2D). However, these differences were small and did not reach statistical significance. The general pattern of results did not change when only selected targets, which contained

mountainous areas and no salient human-made features, were analyzed. The elimination of the most difficult and the easiest trials from the statistical analysis increased the differences between the 2D and the 2_D scores, but this difference too failed to reach statistical significance. Several factors may have affected the potential effects of an overlaid SAR-DTM imagery on the accuracy of target recognition:

The sets of SAR swaths used in the study were rather limited in size and included only small areas which were both mountainous and free of salient human made objects. Hence, the number of sections in which the SAR-DTM overlay could provide significant advantages was rather small and the variety was very limited.

Because of the limited width of each swath and the small variety of useful terrain areas, the size of the area displayed during each trial was significantly smaller than the size of area which IA use in their regular routine. This may have made the use of terrain features more difficult than usual to exploit.

The use of the overlaid SAR-DTM seems to require some training. This was indicated by the results which show a larger improvement in SAR-DTM performance than in SAR alone, and was pointed out by some of the SMEs (in their comments) as well.

Response times were approximately 17 percent longer for the 2_D trials than during the 2D trials. This is not surprising given that the 2_D images contain more information. Additionally, during the 2_D trials SMEs made more extensive use of the tilt option which provided them with different views of the terrain, whereas, tilting the 2D images was possible but did not provide any additional information.

Situation awareness as measured by the questions at the end of each trial did not benefit from the overlay of SAR-DTM. Two reasons may have affected the results. First, the answers to the SA questions could be extracted from the maps as well as from the SAR images. At the end of the experiment SMEs were asked about the extent to which their SA answers were based on the SAR as compared with the map. During debriefing, most SMEs reported that the maps were an equal or a dominant source of SA information. Obviously, the use of the map obscures SAR imagery effects. Secondly, although all IAs considered the SA questions as relevant to their jobs, they also indicated that the level of details required tended to be higher than is usually required on the real “object recognition” job, (e.g., comparing the slopes of two

adjacent domes). Several SMEs indicated that this level of detail would be more relevant for determining traversability. Hence, some of the SA questions were perceived as an additional secondary task rather than as part and parcel of the main target acquisition task.

Individual performance differences were quite large and seem to be related to the level of experience. Interestingly, the more experienced SAR interpreters seemed to have benefited less from the SAR-DTM overlay than the inexperienced SMEs. However, these findings were not significant and require further investigation.

In their subjective ratings at the end of the experiment, SMEs expressed their faith in the potential of the 2_D imagery, as an aid for image analysis, improving SA, enhancing general orientation, understanding the structure of terrain and perceiving height and slope differences.

4.2 Recommendations

Future studies should include exploration of the 2_D SAR and other sensors (e. g., electro-optical), in a fused display format, to support IA confidence in performing SA and information extraction tasks. (This recommendation is based on observation of the SMEs strategies in carrying out the tasks.)

The use of a DTM overlay should be studied in conjunction with various types of sensor imagery under conditions where sensor imagery may disappear or fade out (e.g., passing through a cloud, degraded conditions for thermal imagery). It is hypothesized that under these conditions, the DTM may serve as an anchor, prevent loss of orientation and thus enhance orientation and object recognition performance.

SME training and individual differences may have played an important role in the present study. These issues require further investigation.

5. Acknowledgements

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Force who shared their expertise so willingly with the experimenters in support of this research.

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