SPATIAL DISTORTION AND QUANTITATIVE GEOLOGICAL MAPPING OF MAKHTEH RAMON, NEGEV, ISRAEL, BY USING THE GER 63 CHANNEL SCANNER DATA

RÉSUMÉ
Les données de la vallée de Makhtesh Ramon, à Negav, en Israël, acquis par le scanner de bord GER en juillet 1989 présentent d'importantes distorsions géométriques le long de la direction de balayage transversale, qui affectent leur utilisation pour la cartographie de surface. La géométrie des données du scanner GER a été vérifiée par rapport à une carte géologique au 1/20 000 numérisée et des données SPOT en superposant, d'une part, les images à la carte et, d'autre part, les images entre elles. Les corrections géométriques ont été effectuées en sélectionnant des points de contrôle au sol et en transformant les données GER à l'aide d'une transformation polynomiale (polynômes de premier, deuxième et troisième degré) et de la méthode de triangulation de Delaunay. La méthode de triangulation utilisée avec 125 points de contrôle au sol pour la superposition des images à la carte et 135 pour la superposition des images entre elles a permis d'obtenir les meilleurs résultats pour l'image brute GER. On a utilisé un algorithme de séparation spectrale linéaire pour produire des cartes de constituants minéralogiques particuliers d'une partie de Makhtesh Ramon. Les images GER classifiées, corrigées spatialement pour trois constituants primaires (calcite, dolomite et gypse), offrent, de façon générale, une bonne corrélation avec les unités présentes sur la carte géologique. De petites discordances ont toutefois été constatées. Ainsi, les observations de terrain ont mis en lumière des erreurs à la fois sur la carte géologique et dans les images classifiées. D'autres discordances étaient imputables aux changements saisonniers de la couverture minérale de surface par des alluvions et des dépôts sableux. Les discordances, qui s'expliquent facilement, représentaient entre 10 et 20 % de la surface totale à l'étude. Les résultats montrent que, en dépit de leurs importantes distorsions, les données du scanner GER multibande à 63 canaux se révèlent utiles pour la cartographie quantitative et précise des sites minéralogiques.

SUMMARY
GER aircraft scanner data acquired over Makhtesh Ramon, Negev, Israel, during July 1989 have significant geometric distortions along the cross-track direction that affect the data's use for surface mapping. The GER scanner data geometry was inspected relative to a digitized 1:20,000 scale geological map and SPOT data using image-to-map and image-to-image registrations, respectively. Geometric corrections were made by picking ground-control-points (GCPs) and warping the GER data using both polynomial (first, second, and third degrees) and Delaunay triangulation techniques. The triangulation technique with 125 GCPs for the image-to-map registration and 135 GCPs for the image-to-image registration was found to produce the...
best results for the GER raw image. Linear spectral unmixing (UNM) was used to produce maps of specific mineral components of part of the Makhtesh Ramon. The GER UNM spatial-corrected images for three endmembers (calcite, dolomite, and gypsum) are generally in good agreement with the geological map units. Some small inconsistencies occur between the UNM images and the geological map. Field observations indicated that errors in both geological mapping and UNM classification occurred. Other inconsistencies between the UNM and geological maps were due to seasonal changes of surface mineral coverage by alluvial and aeolian materials. The total inconsistencies were between 10 and 20% of the entire area examined and are easily explained. The results showed that despite its great distortion, the GER 63-channel scanner was a good vehicle for accurate and quantitative mineral mapping.

INTRODUCTION

Imaging spectrometry (IS) is the simultaneous acquisition of images in a large number of contiguous spectral bands, such that for each pixel a complete reflectance spectrum can be derived for the wavelength region coverage (Goetz, 1991). Due to the large amount of spectral information that IS systems provide, the raw data must be pre-processed very carefully prior to meaningful analysis (Simpson, 1992) for obtaining the accurate reflectance of each band. These processes include spectral and radiometric calibrations, removal of atmospheric interferences, and geometric corrections. The spectral calibration of the GER employed a spectrometer band and sensitivity alignment by illuminating the nadir region of the scanner entrance with different sources of lights. The radiometer tests employed a transfer coefficient and signal-to-noise determination for all bands using a calibrated reflectance target (GER Manual).

Unlike the radiometric calibration and atmospheric removal processes, which are critical for extracting a pixel spectrum, geometric correction is not essential if accurate spatial mapping is not involved. As a result, geometric correction of high spectral resolution image data in general and of the GER in particular do not receive the same attention as spectral, radiometric, and atmospheric corrections.

Flight altitude and attitude are major sources of spatial geometric distortion. Defined as non-systematic errors, these include flight altitude and speed, roll, pitch, and yaw, scanner motion and synchronization between ground velocity, and scanner motion (Reimer et al., 1987). In spaceborne platforms, although the altitude is fairly high and the scan angle is low, these errors are quite negligible as compared to airborne platforms that experience air turbulence during almost every flight. However, for airborne platforms where the altitude is relatively low and the scan angle is high, these errors are considerably larger. Aircraft altitude (especially roll, pitch, and yaw) may be corrected by using recorded information of flight parameters (Mackin and Munday, 1988) whereas others require special considerations that are based on the image itself (Bach and Mauser, 1991).

Airborne high spectral resolution imaging spectrometers, such as AVIRIS (Airborne Visible Infrared Imaging Spectrometer, 224 bands in the 0.4–2.5 μm spectral region, Vane et al., 1993) or GER (Geophysical Environmental Research, 63 bands in the 0.4–2.5 μm spectral region, Collins and Chang, 1988) scanners, provide important spectral information for each ground pixel. Although spatial distortion is not considered to be a major problem with the AVIRIS data (because of its high altitude [20 km] and low FOV [30°]), the GER data have marginal geometric characteristics because of low altitude (1–5 km) and high field of view (FOV) of 90°. Role correction based on recorded flight information (system gyro-logged in band #64) is typically applied on a pixel-by-pixel basis to the GER data prior to release to customers (Mackin and Munday, 1988). Although errors other than the roll error still remain in the GER data after this particular correction (Hill, 1991), only limited studies have applied a full geometric correction to their data using image warping algorithms (see, for example, Green et al., 1991; Taranik, 1990; Bach and Mauser, 1991). Hill (1991) used system-corrected GER data of Southern Ardèche, France, corrected for aircraft roll, detector speed, and scanning angles. In other studies (see, for example, Mackin and Munday, 1988), it is mentioned that only the roll correction was performed. Unfortunately in many GER studies, even this limited information is not provided (see, for example, Kruse et al., 1990; Lehmann et al., 1990; Hussey, 1989; Taranik and Kruse, 1989; Kaufmann et al., 1991; Wilson et al., 1991; Rothfus et al., 1991). This may be due to an absence of the flight roll information (band #64), as well as to the fact that workers preferred to concentrate on the radiometric/spectroscopic aspect of the data.

The GER flyover over Makhtesh Ramon, which took place during July 1989 (Kaufmann et al., 1991), suffered from lack of planning and processing (Ben-Dor et al., 1994). No in-flight calibration or corrections (radiometric or geometric) were applied to the raw data and no information was recorded on band #64. As a result, the raw data have received only limited attention by workers who performed advanced analysis methods on the spectral information provided by the detailed GER (see, for example, Kaufman et al., 1991; Bethy and Henkel, 1995). Recently Ben-Dor et al. (1994) were able to effectively radiometrically correct the data by comparing various available atmospheric correction methods. Based on these results, Ben-Dor and Kruse (1996) were able to quantitatively map several minerals using the GER images and linear mixture modeling (UNM) and to quantitatively allocate (1996) the column carbon dioxide and water vapour contents using spectral parameters of the gases' absorption bands. Although, in general, good agreement was found between the GER-UNM images and the major lithological units of a published geological map, and between the gases' images and the area topography, the geometric errors in the analyzed data still prevented them from accurately mapping and producing ground verification of both surface and atmospheric findings.

The purpose of this study was to investigate the magnitude of the geometric distortion of the GER data of
Makhtesh Ramon, Negev, Israel, and to point out the best procedure for correcting this interference. Based on this result, the second goal was to provide GER-UNM images registered to a ground-based information to enable ground and map verification of some important mineral sites at Makhtesh Ramon, Negev, Israel.

**MATERIALS AND METHODS**

Data Characteristics

**GER Data**: GER 63-band scanner aircraft were flown over Makhtesh Ramon, Negev, Israel, during July 1989. The selected flightline was flown with the following characteristics (Figure 1): flight altitude of approximately 4,500 m above sea level (asl), flight direction of 050°, starting local time of 10:50, flight time of 5 minutes, and starting geographic points (in terms of the local Israel geographic system) of 1225,9076. Data were recorded in 16-bit mode, and each cross-track scan consisted of 512 pixels. No pre-processing routines (geometric or radiometric) were applied to the data. System parameters for the whole spectral region (including number of bands, band width, and bond centering) are given in detail by Kaufmann et al. (1991) and Ben-Dor et al. (1994). Two bands (band 28, 0.81 μm; band 32, 1.440 μm) were omitted from the analysis because of their unusual spectral response. Band centering was examined on the basis of known absorption features of the atmospheric carbon dioxide (CO2) located at 2.005 and 2.055 μm. The corresponding CO2 bands were observed in the GER radiance at 2.002 μm and 2.054 μm, confirming the nominal values provided by GER. For the purpose of the following discussion, the spectral regions used are defined as Visible and Near Infrared (VNIR; 0.477–0.848 μm) and Short Wave InfraRed (SWIR; 1.440–2.443 μm).

**SPOT Data**: A SPOT (XS) image of the Makhtesh Ramon area was used as another set of reference data (in addition to the geological map) against which the raw GER data were rectified. The SPOT data received from SPOT-IMAGE company were processed to 1B level (radiometrically and geometrically corrected). We examined the feasibility of the SPOT to be an alternative correction source for the distorted GER data in areas that have no mapping information.

The current SPOT data were acquired on December 13, 1990. Scene starting and ending times were 08:30:12.692 and 08:30:21.716, respectively. Sun azimuth angle was 162.30°, sun elevation was 34.38°, and incidence angle was 10.14°. The SPOT satellite had an altitude of 832 km and a site angle of -2.22° for this particular scene.

**Software Used for Image Processing**

The Spectral Image Processing System (SPS, v. 1.2) developed at the Center for Study of Earth from Space (Kruse et al., 1993) was used to read and process the GER and the SPOT data. This package provides many interactive analysis tools for image spectroscopy, such as data subsetting, several atmospheric correction techniques, image display and enhancement, color compositing, selection and display of image spectra, and hyperband data manipulation. Several other routines written in the Interactive Data Language (IDL®; Research System Inc., 1992) were used to perform the registration, warping, and overlapping procedures.

**Atmospheric Correction and Image Subsetting**

The Internal Average Relative (IARR) method (Kruse, 1988) was applied to the GER raw data to provide atmospherically corrected data transferred to “apparent reflectance.” This method was selected based on recommendations by Ben-Dor et al. (1994) and Ben-Dor and Kruse (1995) regarding this particular flight. Only a part of the Ramon-2 flightline was used for this study (called subset Ramon-2 [b]). This subset was selected to cover most of the area covered by the geologic map of Zak (1968) and the GER-UNM images of Ben-Dor and Kruse (1995).

**Digitizing the Geologic Map**

A 1:20,000-scale geologic map (Zak, 1968) covering most of the GER and SPOT subset areas was used to register the GER data. First, the map was digitized using the ARC/INFO geographic information system (GIS) software (Environmental System Research Institute, 1988). The digital line map was then transferred into the image processing environment as a rasterized line map corresponding to the GER and SPOT images. Two procedures for transforming the digital map into the image coordinates were performed: transformation to the GER image size; and transformation to the SPOT image size.

- The transformation to the GER image coordinates was performed by using a constant pixel size value of 17.4 m.
- This pixel size was obtained by averaging several GER pixels that were determined using the distance of well-defined ground points on both the GER raw image and the digital map. This pixel size value (X=17.4 m, Y=18 [num-
ber of pairs of ground points used to determine the average pixel size of the image - X, SD=2.4 [Standard Deviation of X] is quite different from the GER spatial resolution at nadir (13.44 m) that Kaufmann et al., (1991) claimed for this particular flight, and supports the need of the geometric correction of these data.

- The transformation into SPOT image coordinates was performed by using a constant pixel size of 20.7 m. This pixel size was determined from the SPOT data in the same fashion as for the GER raw pixel size (see the first stage, above). The pixel size of the SPOT image (X=20.7 m, n=5, SD=0.5) is very close to the SPOT spatial resolution that the SPOT IMAGE company claims for its multi-band data (20 m) and suggests that the SPOT data is geometrically uniform.

Interactive Data Processing and Analysis

Geometric Correction

Overview: Geometric correction and removal of non-systematic error distortions can be done by using ground control points (GCPs) and well-rectified data. Image warping techniques transform the uncorrected image data into a corrected set of data. The ground points registration selection is done using image-to-image tie points, image-to-map tie points, or image-to-vector tie points (Bernstein et al., 1985; Lillesand and Kiefer, 1987). Polynomial and Delaunay triangulation warping techniques are mathematical models that use the GCPs to transform the raw image into a new, corrected image. The polynomial procedure requires a fit of polynomial equations to the GCPs using least-squares criteria to model the corrections in the image domain without identifying the source of the distortions (Akima, 1970). The triangulation procedure corrects the image by transforming the GCPs into a new Euclidean plane that consists of polygons whose vertex points are the circumcentres of the triangles defined by three GCPs (Lee and Schachter, 1980). In both transformation procedures, resampling the pixel values can be accomplished by three methods:

- Nearest neighbour interpolation assigns the grey-level value of the closest pixel to the input coordinate specified, to the output coordinate. This method does not alter the grey-level value but can contribute small radiometric errors into the output image (spatially offset by up to 1/2 pixel)
- Bilinear interpolation takes the four pixel values nearest to the desired pixel position in the input image and calculates a new grey-level value based on the weighted distances to these points. This technique generates a smoother resampled image but alters the grey-level values
- Cubic convolution interpolation is similar to the bi-linear technique except that the weighted values of 16 input pixels surrounding the location of the desired pixel are used to determine the value of the output pixel. This method avoids the disjointed appearance of the nearest neighbour method and provides a sharper image than the bi-linear method. Again, however, this method alters the grey-level values.

Current Use: To perform the geometric correction of the GER raw data of Mahesh Ramon, we ran two different registration processes: image-to-map registration (using the raster representation of the geologic map), and image-to-image registration (using the rectified SPOT data).

Image-to-map registration was first applied to GER raw data using the map image. A grey scale of the GER raw image (band #6, 2.151 μm) was used for registration. Prior to the registration, the map image was rotated to generally match the orientation of the GER raw image. GCPs representing easily recognized geological features visible in both the map and GER images were interactively selected on the display using an Interactive Data Language (IDL®) (Research System Inc., 1992) procedure designed for quick picking of image control points. Registration quality was ensured by selecting GCPs that provided RMS error values lower than 13.4 m (~1 GER pixel). The GER image was warped to match the map image using the two warping techniques described above (polynomial first, second, and third order) and triangulation. Both warping algorithms were run after each additional five GCPs were selected. The quality of the warped image result was inspected by using interactive overlapping images and “flickering” the corrected GER and source map images. The best geometric correction was obtained by using the triangulation transformation with 125 GCPs. The intensity interpolation of the current image employed the nearest neighbour resampling technique.

Image-to-image registration was applied to the GER raw data using a subset of the SPOT image that covers the GER scene (and hence the geological map). For the registration process, grey-scale images of both GER (band #1) and SPOT (band #2) were used to register the images. Prior to the registration, the GER image was rotated to match the general orientation of the SPOT image and the GCPs were again selected. The selection of GCPs was again done using well-defined ground locations present in both the GER and the SPOT images. Registration quality was inspected by selecting GCPs that provided RMS error values lower than 10.1 m (~1/2 SPOT pixel). The GER image was warped using the two warping techniques described above. Again, both warping algorithms were run after each additional five GCPs were selected. The quality of the warped image result was inspected by using interactive overlapping images and “flickering” the corrected GER and source SPOT images. The best geometric correction was obtained by using the triangulation transformation with 135 GCPs. The intensity interpolation of the current image employed the nearest neighbour resampling technique.

For both registration procedures, the Delaunay triangulation transformation yielded the best rectification results (lowest RMS and good visual judgement). Devereux et al. (1990) concluded that the polynomial transformation can only deal with a limited number of relatively smooth changes in image geometry, not large numbers of abrupt local changes, and that the method does not guarantee a correct transformation even at GCP locations. Devereux et al. (1990) showed that the Delaunay routine has the capacity to cope with more complex patterns of distortion at high frequency and thus proves superior to traditional polynomial-based methods for correcting airborne scanner data.
The current data set stands under the condition described above and hence required the sharp warping method that could only be provided by the triangulation method. Another example of the success of the triangulation method in warping airborne scanner data with large FOV (about 70°) is provided by Chen and Rau (1993).

Linear Unmixing (UNM)

Overview: Spectral unmixing (UNM) is a method for determining the fractional abundances of each endmember that can best account for the observed mixed spectrum at each pixel. It assumes that the reflectance of a given target is a combination of each of the target components reflectance ("endmembers"). Various models (linear and non-linear) may be used to determine the contribution of each endmember to the overall spectrum (Singer and McCord, 1979; Johnson et al., 1983; Mustard and Pieters, 1987). In nonlinear mixing, an incoming photon is scattered by more than one component within the surface, whereas in linear mixing none of the photons encounters more than one material at a time (Goetz, 1992). Non-linear models may be linearized through transformation to single scattering albedo, and therefore all commonly used computational models rest on the assumption that the observed spectral radiance may be modelled as linear combinations of pure "endmembers" (Smith et al., 1985; Boardman, 1989, 1991; Boardman and Goetz, 1991). The basic model may be presented as follows:

\[ A^T \times X = B \]

where \( A \) is an \( m \times n \) matrix of library spectra, \( X \) is an \( n \times 1 \) vector of abundance, and \( B \) is an \( m \times 1 \) observed data vector. Inverting the library matrix allows the calculation of a vector of the endmember abundances:

\[ X = A^{-1} \times B \]

Current Use: To perform the unmixing procedure on the Makkesh Ramon GER data, we created a GER spectral library of nine endmembers. Calibration procedures and details of the selection of the endmembers are described in Ben-Dor and Kruse (1995). Basically, the selection was performed by choosing areas on the image that provide spectra that match library spectra of well-known minerals. Linear combinations of the selected endmember spectra were applied by using the linear method described in Boardman (1991) to yield a best-fit spectrum for each pixel. The error between the original, mixed spectrum (GER-calibrated spectrum) and the best-fit spectrum was determined for each pixel. The root-mean-square (UNM-RMS) method was used to determine the difference, or error, between each observed spectrum and the spectrum reconstructed from the calculated abundances. The linear sum of all spectral combinations of the selected components was also calculated. We used the fully constrained algorithm (Smith and Adams, 1985; Boardman, 1991), which places the additional constraints that abundances must be non-negative and that the sum of the abundances must be less than or equal to one (100%). The unmixing output is a cube with the same spatial dimensions as the input cube (therefore containing its original geometric distortions). The cube contains one image for each endmember, representing the fractional abundance of that endmember scaled from 0% to 100%.

RESULTS AND DISCUSSION

The location of Makkesh Ramon in Israel and the exact coverage of the current study are presented in Figure 2. Basically Makkesh Ramon is a valley surrounded by steep walls, eroded into an anticline fold and drained by a single river (Nahal Ramon). Makkesh (mortar in Hebrew) Ramon is 40 km long and about 12 km wide. The highest point on the rim, Har Ramon, has an altitude of 1020 m asl, and the lowest point at the outlet of Nahal Ramon is 420 m asl. Exposed geologic units include marine, continental, igneous, and volcanic rocks of the Triassic to Upper Cretaceous (Nativ and Mazor, 1987). A schematic transect along the center of Makkesh Ramon (after Ben-David and Mazor, 1988) showing the approximate coverage of the GER scanner is presented in Figure 1. A more detailed geological description of Makkesh Ramon is given by Kaufmann et al. (1991) and Ben-Dor et al. (1994).

The geological map of the study area digitized directly from Zak's map (1969) is shown in Figure 3, while the details of each of the geological units shown are described in Table 1. The raw GER (band #45) and a subset of the SPOT (band #2) image that cover Zak's geological map (1968) are shown in Figures 4 and 5. To compare the geometric distortion between the GER and the SPOT images, we superimposed the geological map on both uncorrected images. The geological map boundaries overlain on the raw GER image are presented in Figure 6a. Because of large geometric distortions in the GER data, it was impossible to obtain a perfect match between the map and the image. We fit, as much as possible, the location of Nahal-Ramon on the right side of the image. It is easy to observe from Figure 6a that other
Table 1. Description of the geological mapping units presented in Figure 3.

<table>
<thead>
<tr>
<th>Mapping Unit*</th>
<th>System</th>
<th>Series</th>
<th>Group</th>
<th>Formation</th>
<th>Lithology</th>
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</thead>
<tbody>
<tr>
<td>K1</td>
<td>Cretaceous</td>
<td>Upper</td>
<td>Judea</td>
<td>Hatsera</td>
<td>limestone, chert</td>
</tr>
<tr>
<td>Kuh</td>
<td>Cretaceous</td>
<td>Cretaceous</td>
<td>Judea</td>
<td>Hatsera</td>
<td>limestone, marl, chert, cross-bedded sandstone, clay</td>
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<td>Ji</td>
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<td>Lower Middle-</td>
<td>Innar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ja2</td>
<td>Jurassic</td>
<td>Cretaceous</td>
<td>Ardon</td>
<td></td>
<td>dolomite, clay</td>
</tr>
<tr>
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<td>Jurassic</td>
<td>1</td>
<td>Ardon</td>
<td></td>
<td>dolomite, clay, conglomerate</td>
</tr>
<tr>
<td>TR(m1,m2c,m3c)</td>
<td>Triassic</td>
<td>Neotrias</td>
<td>Ramon</td>
<td>Mohila</td>
<td>gypsum, cellular limestone</td>
</tr>
<tr>
<td>TR64</td>
<td>Triassic</td>
<td>Neotrias</td>
<td>Ramon</td>
<td>Saharonim</td>
<td>gypsum, marl, limestone</td>
</tr>
<tr>
<td>TRm3</td>
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<td>Neotrias</td>
<td>Ramon</td>
<td>Mohila</td>
<td>gypsum, gypsum, clay</td>
</tr>
<tr>
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<td>Neotrias</td>
<td>Ramon</td>
<td>Mohila</td>
<td>gypsum, andesite, limestone</td>
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<tr>
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<td>Neotrias</td>
<td>Ramon</td>
<td>Saharonim</td>
<td>gypsum, marl, andesite</td>
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<tr>
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<td>Ramon</td>
<td>Saharonim</td>
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<tr>
<td>r</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>essesite, andesite</td>
</tr>
<tr>
<td>v</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>nordmarkite, bonolite</td>
</tr>
</tbody>
</table>

*According to Zak, 1968.
areas on the GER image are totally distorted versus the geological map. Quantitatively, it can be observed that the south-west wall of the Makkhesh (left side of the image) in the GER raw image is offset about 2000 m relative to the map (see arrows on Figure 6a). Note in the GER raw image that the cross-track distortions are quite large, whereas the along-track distortions are relatively small. These observations suggest that the errors of the GER raw data may result from two sources: systematic errors associated with the panoramic and non-linear scan velocity effects (Bernstein, 1983) as well as relief displacement (Devereux et al., 1990); and errors caused by changing topographic relief that occur mostly on the left (south-west) side of the image (see Figure 4). It seems probable that both factors play some role in the distortion of the GER raw data.

Using the Delaunay triangulation and 125 GCPs, we warped the raw GER image to match the digitized map. The GER map-corrected image with the geological map boundaries overlain is shown in Figure 6b. The triangulation warp method does not do well at correcting areas outside the GCP space (Lee and Schachter, 1980). Thus, we cut the map-corrected image to conform to the geological map coverage. Most of the geological unit boundaries on the map match apparent lithologic boundaries presented on the map-corrected GER image (see Figure 6b). The effect of the cross-track distortion (shown in Figure 6a) has been reduced to a minimum, as no offset can be observed on the south-west wall of the Makkhesh.

The raw SPOT image with the geological map boundaries overlain is presented in Figure 7a. Only small geometric distortions can be observed in both cross- and along-track directions. Image-to-image registration usually consists of errors associated with the reference image and therefore is not always recommended. In cases where the reference image is well rectified, it is important to study the image-to-image registration quality. This is because registration to a (geological) map is a quite complicated and time-consuming task, whereas image-to-image registration (SPOT-to-GER in this case) allows more accurate selection of GCPs (based on a similar view format obtained by SPOT and GER images), which may increase the overall accuracy. To study this idea further, we used the image-to-image GCP selection and registered the GER raw image (band #45) to the SPOT image (band #2). By using the same routines used previously for the image-to-map registration, we found that Delaunay triangulation using 135 GCPs provided the best match. The GER image (corrected using the SPOT image) with the geological map overlain is shown in Figure 7b. Good agreement is again achieved between the boundaries of the geological units on the map and the apparent lithologic units shown on the corrected GER image. RMS error of 10.1 m for the image-to-image registration is somewhat less than that for the image-to-map registration (13.4 m), but both are reasonable for correcting the raw data.

**UNM Mapping on the GER Map-Corrected Images**

To examine how the UNM results relate to the geological map of Makkhesh Ramon, we used the warping procedure and GCPs used for the raw GER band #45 data to warp the UNM images by using the image-to-map registration. Be-
cause warping the image may change the DNs of the output image (Bernstein et al., 1983), the warping procedure took place only after the UNM procedure was applied to the GER data. The UNM images (for each endmember) were geometrically corrected only after the UNM analysis was completed. Three endmembers were selected for correction: calcite, dolomite, and gypsum. The UNM images of each of the above endmembers with the geological map boundaries overlain are shown in Figure 8. The coloured geological map of Makhtesh Ramon is shown for direct comparison (see also Figure 3 and Table 1).

The match obtained between the geological map units and the endmember distribution obtained by the UNM analysis is remarkable. This can be quality judged by viewing both the GER-
corrected images and the geological map in Figure 8. For a more accurate examination we applied a quantitative measurement of the UNM results by comparing the area that each of the endmembers occupied in the corrected image (using a minimum threshold of 60% in the UNM analysis) relative to the corresponding geological unit’s area in the geological map.

Calcite (green on the map) appears in Kuh, Ku2, Ku1 (limestone from Hatsera formation), and Kum (chalk from Meruha formation). The UNM calcite area occupied about 78% of the corresponding units in the geological map, whereas no UNM calcite areas were found outside the calcite’s map boundaries; dolomite (blue on the map) appears in Jai, Jai2 (Ardon formation), and TRn3 (Mohila formation). The UNM dolomite area occupied about 82% of the corresponding units in the geological map, whereas about 10% of the UNM dolomite areas were found outside of the dolomite’s map boundaries; gypsum (purple on the map) appears mostly in TRn2 (Mohila formation) and partially in TRn3 (Sharonim formation). The UNM gypsum area occupied about 80% of the corresponding units in the geological map, whereas about 10% of the gypsum areas were found outside of the gypsum map boundaries (see Figure 3 and Table 1 for details). The relatively good agreement between the geological map and the UNM map-corrected images suggests that the UNM technique worked well for the current GER data. The selection of each endmember was based on the GER spectra of several ground locations and their match to laboratory spectra (Ben-Dor & Kruse, 1985). The excellent match between units obtained here also supports the validity of the atmospheric correction method (GARR), which Ben-Dor et al. (1994) recommended for these particular data.

Careful observation of the UNM images shown in Figure 8 indicates some small areas of inconsistencies (marked with purple horizontal lines) between the geological map and the GER UNM map-corrected images. These inconsistencies may occur because of the fact that only the upper 50 μm are observed by the GER sensor (and all other VIS/NIR/SWIR instruments). Disagreement may result from coverage with aeolian or alluvial materials that may have changed from when the geological map was compiled (1968) and the GER flight was made (1986). Other inconsistencies can be attributed to field (hence, map) errors, as well as to errors in the UNM analysis within these small areas. Field observations actually confirm the above explanation as follows: for the gypsum case, the strong inconsistency spot in the north side of Biqat Mishor (see Figure 3) is a result of a large “dust cloud of kaolinite-gypsum materials released into the air by an industry grinding process that takes place in this area.” Other gypsum inconsistencies, concentrated on the southern part of the image, are located on Nahal Nekarot. This dry creek actually drains the Makhtesh area via Nahal Ramon during rainfall events, and the gypsum spots are the result of alluvial transportation of kaolinite-gypsum materials washed out from the heart of the Makhtesh Ramon crater. In the case of the dolomite image, two inconsistency cases were observed. In the first case we found a mixed calcite-dolomite formation in areas where the geological map indicated pure calcite. In the second case (a small area at Har Shen Ramon), where no dolomite formation is actually found on either the ground or the geological map, the dolomite spots are considered to be a UNM analysis error. In the calcite UNM image case, we found on the ground a “clay” lens (in the left lower side of the image) that perfectly matches with the image but not with the geological map. We consider this inconsistency to be a geological mapping error.

It can be concluded that a combination of sophisticated spectral analysis and careful geometric correction of high spectral and moderate spatial resolution data such as the GER data provides great promise for verifying existing maps, as well as for producing new maps that show mineral abundances.

SUMMARY AND CONCLUSIONS

The raw GER data of Makhtesh Ramon exhibit extreme geometric distortions in the cross-track direction. These distortions are the result of the high FOV and low flight altitude of typical GER missions, combined with the effect of high relief in parts of the study area. Based on the offsets obtained between the raw GER image and the boundaries of the geological map, it is recommended that all GER 63-band scanner data be geometrically corrected prior to mapping and interpretation use. The GER geometric distortions can be corrected by image-to-map registration or, preferably, by image-to-image registration using SPOT images. Image-to-image registration has the advantages of rapid registration and accurate selection of the GCPs. The Delaunay triangulation algorithm, with more than 100 GCPs, produces the best results for both registrations. Good agreement is obtained between the UNM results and the geological map of Makhtesh Ramon. Some inconsistencies between the geological map and the GER UNM map-corrected images occur within small areas. These inconsistencies were the result of surface changes, UNM analysis errors, and field mapping errors. It is obvious that geometric correction of the GER raw data allows better comparison between ground maps and analytical data derived from the raw GER images. It can be concluded that, although the GER data exhibit extreme distortion and no information about the airplane motions was provided at the time of acquisition, GER data can still provide a powerful tool for accurate mineral mapping, if careful consideration is given to correcting the geometric errors.

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