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ERTS Color Image Maps *

USGS has developed useful lithographic products from multispectral scanner data obtained by satellite.

Abstract: *The U.S. Geological Survey has prepared several experimental color-image maps from Earth Resources Technology Satellite* (ERTS-1) *images. Examples are the gridded image of Upper Chesapeake Bay and the mosaic of New Jersey. Both were printed at a scale of 1:500,000 with a full UTM grid and placed on public sale in February 1974. A color mosaic of Florida is being prepared from 16 separate scenes. It also will be printed at 1:500,000 scale. The publication of maps from satellite images has required the development of innovative procedures combining computational photogrammetry, image geometric control, photomechanical mosaicking, and color lithography. These color-image maps are the first to meet cartographic standards and to be lithographed for public sale at a nominal charge. The detailed procedures and equipment are described, along with some of the results.*

Introduction

The first Earth Resources Technology Satellite (ERTS-1, launched on July 23, 1972, carries two imaging sensor systems. One is the Return Beam Vidicon (RBV), a multispectral television system with three frame-format TV cameras. The other is the Multispectral Scanner (MSS), a four-channel system which continuously scans transverse to the satellite's orbital track. Several descriptions of ERTS and the RBV and MSS systems have been published; the *ERTS Data Users Handbook*[4] is an excellent reference.

Before launch it was anticipated that the RBV would have slightly better ground resolution and considerably better geometric fidelity than the MSS. Considerable geometric calibration data[7,9] were obtained for the RBV, and photogrammetric accuracies of 50 m can be obtained for planimetric positions on a single image. Unfortunately the RBV was shut down shortly after launch due to a switching problem in a control circuit. Although the RBV could probably be operated through an alternative control sequence, NASA has elected not to risk the almost perfect functioning of the MSS and other ERTS systems.

The MSS has exceeded the most optimistic predictions and has produced thousands of nearly flawless images. The image quality is excellent, and the geometric distortions are surprisingly small.[8] With increasing experience, distortion analysis techniques have been developed to reduce or control the distortions still further. The largest error is a displacement between the NASA-published position of an image center and the true location. It may amount to 2 to 5 km and is generally due to the uncertainties of the satellite attitude measurement system. The NASA annotations of latitude and longtitude of the system-corrected (bulk) images are correspondingly affected. The remaining distortions are generally less than 250 m *rms*, and recent results of about 125 m *rms* have been achieved with experimental images processed on the electron beam recorder (EBR) using the conformal algorithms of the Space Oblique Mercator projection[3]. Distortions of this magnitude are negligible for many qual-

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itative analyses of the images. They become significant in attempting to prepare a map or a mosaic of images or if attempting to address in a computer the pixels of the same geographic location obtained on different dates.

Often overlooked is the considerable advantage of the regularity of the ERTS orbit. Not only is nearly worldwide coverage available, but the repeating cycle of 18 days allows a reliable index of images within a regular geographic grid of standard nominal scenes. Although the present orbit occasionally drifts excessively before NASA adjustment, it would be possible to ensure that any image is within 13 km crosstrack and 5 km alongtrack from the precomputed nominal scene centers. This provides a regular repeating sequence of images over defined geographic areas and is one of the most powerful advantages of the ERTS system for studying Earth resources.

The U.S. Geological Survey (USGS) has several ERTS cartographic experiments to evaluate photomapping, map revision, thematic mapping, polar mapping, orbital data evaluation, and the overall cartographic application. A continuing program is in operation to evaluate the geometric accuracy of single images and photogrammetric blocks. In addition, a program exists for preparing ERTS color-image maps for public distribution at a nominal charge.

ERTS Nominal Scenes

The ERTS orbit has three major characteristics which will become increasingly important for automated image mapping. The first is the sun-synchronous precision due to the plane of the satellite precessing at the same rate as the mean rate of the Earth's revolution about the Sun[4]. The orbital plane is at a constant angle to the Sun as the Earth circles through the seasons of the year. Thus the satellite is always imaging areas of a given latitude at the same local (Sun) time. Second, the ground tracks for all orbits on a given day *N* are displaced westward 159 km at the Equator from the respective orbits on the preceding day *N-1*. This displacement provides a predictable sidelap of the images; it is 14 percent at the Equator and increases with latitude due to the convergence of the ground tracks toward the poles. Third, the orbital period of 103.267 min is the exact interval required for the ground track to retrace itself every 251 orbits (18 days). Orbit *R +251* occurs 25,920 min (18 days) after orbit *R*, and the daily rotation of the Earth causes the orbit to pass over the same ground tracks. This regularity permits a comprehensive set of only 251 nominal ground tracks to be plotted on a map of the Earth with assurance that all actual orbits will repeat on the nominal tracks. This characteristic is of profound importance and beautiful simplicity. It permits an organized, regular system of indexing and mapping that could form the practical basis for an automated mapping system.

With the nominal ground tracks determined, it is logical to establish a framing sequence for the images. The RBV has an inherent framing cycle of 25 sec dictated by satellite orbital parameters and instrument field-of-view. This exposure interval produces images covering 185 km by 185 km on the ground and spaced 159 km on center. There is 26 km of overlap from one image to the next in the same orbit. The sequence of exposure stations is initialized at the time of southbound Equator crossing and used to center the controlling frame. All RBV exposures north and south of the Equator are equally spaced at 25 sec time or 159 km of groundtrack distance. This establishes a set of nominal image-center coordinates along the nominal ground tracks; these can be computed and plotted on a map.

The MSS is a continuous scanning device which creates an adjoining series of scan lines transverse to the orbital direction. The length of a single scan line is 185 km on the ground, but the alongtrack scan width is only 79 m. Assembly of sequential scans creates a continuous strip of imagery 185 km wide and centered on the ground track. There is no inherent frame sequence for the MSS. In printing the MSS images on 70-mm film in the EBR, an artificial frame is created. Each frame is centered on the exposure station previously defined for the RBV. The artificial frame covers 175 km alongtrack. As the RBV exposure stations are 159 km apart, an artificial overlap of MSS frames is afforded amounting to 16 km. This overlap is not from two separate observations of the same ground area from two exposure stations as is common with aerial frame-format photographs; it is rather the result of writing some of the MSS scan lines twice, once on each of two adjacent artificial frames. Consequently, the MSS does not have alongtrack stereocapability but does have sidelap stereo where coverage from one orbit sidelaps the adjoining one.

USGS has defined a series of nominal ERTS scenes based on the repetitive coverage of the ERTS ground tracks and framing sequence. The geodetic coordinates of all nominal image centers were obtained from NASA, and a nominal scene formed by lines drawn midway between the centers as shown in Figure

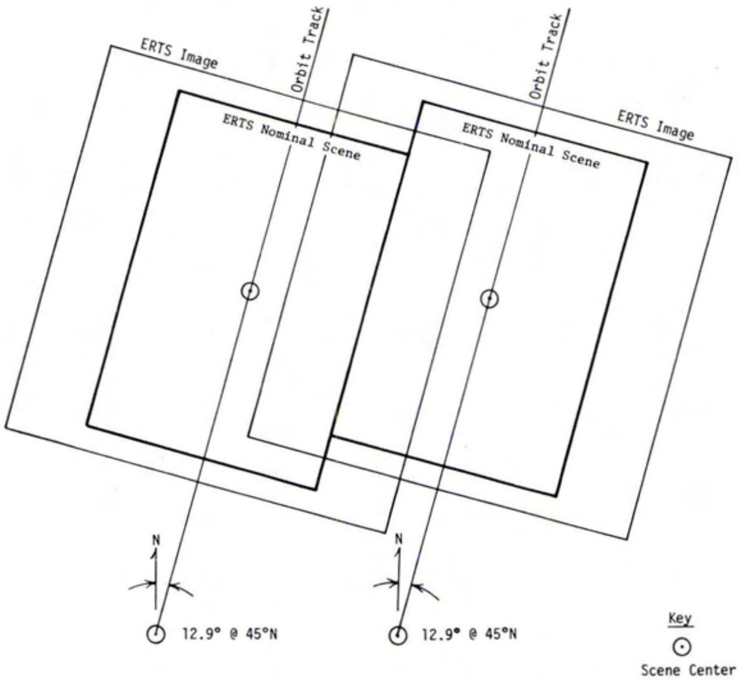

FIG. 1. ERTS nominal scenes at 45° latitude.

1. The nominal scenes are areas on the Earth that, if plotted on a map, create a unique set of pigeonholes for all the Earth covered by ERTS-1. An example for Florida is shown in Figure 2. There is no overlap between nominal scenes and therefore no ambiguity about which scene covers which area. Actual images obtained on the 18-day repeating cycle will generally center on the nominal scene and will overlap adjacent scenes. The amount of image overlap alongtrack is constant as described for the RBV and MSS, but the sidelap between orbits varies with latitude. It is about 13 km at the Equator and 32 km at 40° latitude. The actual drift of the orbit will also affect the sidelap between images from different 18-day cycles.

The unique identification code for each bisector scene is based on the geodetic coordinates of the scene center. The 11 alphanumeric characters specify north or south latitude and east or west longitude in degrees and minutes. The system can be used worldwide and is both human readable and computer compatible.

IMAGE FORMAT MAPS

The first ERTS image format map printed in a color lithographic edition was the Lake Tahoe Area, California-Nevada. It was prepared by the USGS in September 1972, from scene E1002-18131 acquired on July 25, 1972, two days after launch of ERTS-1. A set of random-dot lithographic plates was prepared from the NASA Data Processing Facility (NDPF) scene-corrected (precision) image bands 4, 5, and 7 at 1:1,000,000 scale. The scene-corrected images are transformed by NASA to ground control on the Universal Transverse Mercator (UTM) projection, and the coordinate values are marked on the image border. A fine-line grid was added by connecting the border marks. When the grid coordinates of test points were checked against ground coordinates, the map complied with National Map Accuracy Standards (NMAS).

The two immediate advantages of using single ERTS images to define a map series are the inherent register between MSS spectral bands and the elimination of mosaicking between separate images. The system of nominal scenes, previously described, allows a series of ERTS image-format maps to be prepared. Each ERTS image covers 34,225 km^2 (about the same area as two 1:250,000-scale maps).

The second image format map, Upper Chesapeake Bay, was printed by the USGS in January 1974 from NASA image 1080-15192 acquired October 11, 1972. The map re-

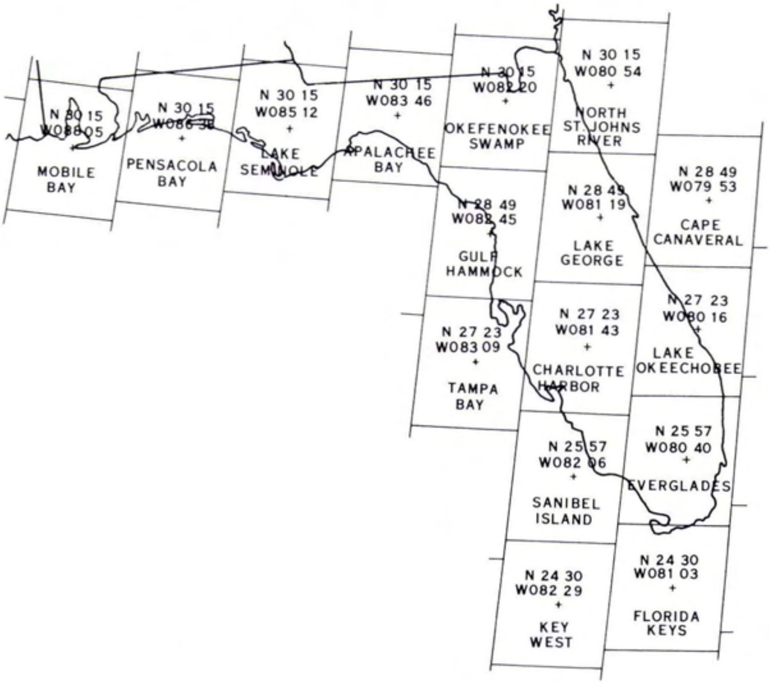

FIG. 2. ERTS-1 nominal scenes in Florida.

quired about a calendar month of production time after the final design was completed. It was the first ERTS map with a completely designed and specified cartographic collar. The collar includes a location map in color prepared from portions of the 1:2,000,000-scale plates of the National Atlas. There is also an index to nominal scenes and the 1:250,000-scale line maps of the area. If possible, an image map should be used in conjunction with a line map.

First-generation 70-mm film copies of the four MSS bands were precisely enlarged to 1:500,000 scale. No photogrammetric rectification was permitted because perfect band-to-band register of the enlarged image requires simple enlargement. It is impossible in practice to place two images on a tilted rectifier plane in exactly the same position. Fortunately, rectification was unnecessary because earlier analytical investigations showed that the distortions could not be reduced significantly by rectification. Two control points were used as a nominal scale line, and after the proper enlargement factor (about 6.74×) was established by trial, all four spectral images were enlarged with the same enlarger setting. Most cartographic enlargers have a wide enough range to enlarge the 70-mm film to 1:500,000 in one step.

Previous geometric evaluation[2] of image 1080-15192 indicated a root-mean-square (*rms*) distortion of 192 m if imaged control points were compared in a conformal adjustment to true UTM values. This error could be expected in the 1:500,000-scale enlargement. In practice the error would be larger due to scaling and photographic lens distortions. To reduce the effect of the image distortion and scaling errors, a procedure of cartographic grid fitting was established[1]. On the band 5 enlargement at nominal 1:500,000 scale, a set of control points was measured throughout the image. The points could be photoidentified and correlated to known features on 1:24,000-scale published maps. UTM coordinates were scaled from the map with an accuracy of about 10-20 m. The grid-fitting program used the ground control points to compute a least-squares set of UTM grid intersections for the image, and a 20,000-m grid was formed by connecting the intersections. One characteristic of the grid computation program is straight grid lines; they may be slightly nonparallel and of slightly different spacing, but the difference from perfect squares cannot be detected with the naked eye. Moreover, any UTM coordinates measured from the nearest grid intersection will be highly accurate. Where applicable, this is the recommended way to use any printed (gridded) map because paper shrinkage can amount to several per cent. The *rms* errors of points measured from the fitted grid was estimated to be 150 m. This finding was checked and confirmed on the final printed copy. It represents excellent cartographic quality for an image map prepared from bulk ERTS imagery.

Other image-format maps are in preparation. Each map is identified by its latitude and longitude code and in addition is given a distinctive name, for example, Upper Chesapeake Bay. The names selected are approved by the Domestic Names Committee of the Board on Geographic Names. Usually major water bodies are favored for a name because they show the greatest contrast and are quickly recognized. In addition, the states covered by the nominal scene will be included in future map names.

Almost all color composites of ERTS multispectral images have adopted the false-color convention of color-infrared film[5]. Although human vision can differentiate many thousands of color variations, the individual detectors of the eye only respond to three primary colors; all other colors are mixtures of the primary colors: blue, green, and red. Thus any printed color image must assign the primary colors in some rational way.

Color-infrared film is commonly filtered to exclude the waveband from 0.4 to 0.5 μm that we call blue, and adds an emulsion layer sensitive to the near-infrared waveband (about 0.7 to 0.8 μm) for which the eye has no sensitivity and experience has assigned no color response. The film has two other layers sensitive to the wavebands 0.5 to 0.6 μm and 0.6 to 0.7 μm which we normally call green and red. However, the dye color introduced into the layers provides a color shift from green to blue, red to green, and infrared (invisible, no color) to red.

This conventional assignment of false colors was not haphazard but rather for the special purpose of camouflage detection during World War II. Increasing civilian use of the film has preserved the color convention for several major reasons:

- Healthy vegetation appears in shades of red and contrasts with unhealthy vegetation appearing blue-green.
- Water appears dark blue or black unless sediment laden where it takes on a light blue tone.
- Most cultural features appear as a steely blue-gray.

The experience of many image interpreters has shown that the convention described provides the best separation of the major themes of vegetation, water, and culture. Other false-color combinations are possible and may have practical or esthetic advantages in special situations. However, the evidence for the conventional false-color rendition is well established for general ease of image interpretation. For example, vegetation, or the lack of it, which is the predominant theme on any earthly scene, is assigned a color variation between red and blue-green.

The MSS on ERTS has four spectral bands as follows:

Band 4	0.5 to 0.6 μm
Band 5	0.6 to 0.7 μm
Band 6	0.7 to 0.8 μm
Band 7	0.8 to 1.1 μm

(Bands 1, 2, and 3 designate the three RBV cameras.) MSS bands 4, 5, and 6 correspond to the three emulsion layers on color-infrared film. Band 7 extends slightly further into the infrared wavelengths and has provided a high-contrast image between water and vegetation. Most ERTS false-color composites have used bands 4, 5, and 7, with band 4 modulating blue light, band 5 modulating green light, and band 7 modulating red light.

The Upper Chesapeake Bay image-format map was printed according to the false-color rendition just described. However, two points may require clarification. On the map collar the MSS spectral bands are listed and are followed by a small color dot to indicate the ink used for printing that band. This was done to provide a permanent scientific verification, integral to the map, of the ink colors and band assignments. However, the curious observer suddenly finds to his surprise that instead of the expected blue dot following band 4, a yellow dot appears. The answer to this apparent anomaly is found in the subtractive technique of color printing, also used for color photographic products[6].

The second point requiring clarification on the Upper Chesapeake Bay map is the use of band 6 for a black-ink plate, which was done experimentally to darken the water tones and increase contrast. Actually it provided very little image tone, and the use of a band 6 black-image plate probably will not be continued.

Map Mosaics

The first printed color ERTS map incorporating more than one image was the state mosaic of New Jersey. It was assembled from three images of a single orbit, numbered E-1079-15124, E-1079-15131, and E-1079-15133, acquired on October 10, 1972 (the day before the orbit that produced the image used for Upper Chesapeake Bay). It illustrates the condition where a large area enjoying several days of clear weather can be completely imaged if the orbital cycle coincides. The joining of the images was aided by the continuous scan pattern of the MSS along the orbit. The mosaicking procedure was novel; film transparencies rather than paper prints were used at every stage.

The major drawback to paper-print mosaics is the loss of resolution of photographic papers which becomes extremely serious with color prints. The prints also lack dimensional stability; indeed, stretchable materials are often needed to match adjoining images. The geometric quality of a paper photomosaic does not usually approach that of a true map. The individual stretching and fitting of images in a black-and-white paper-print mosaic is a permanent obstacle in considering a color-image map. The individual mosaics of separate bands can never be exactly registered and must always be handled as a single-band product. Some of the dimensional inaccuracies can be compensated by fitting a map grid as previously described.

The use of color print materials creates an additional problem if lithographic production is desired. The color mosaic on photographic paper must be color separated into the three primary colors to prepare the separate lithographic halftone plates. Thus the separate MSS spectral bands would be color-combined to a photographic color print, and then color separated to form the printing plates — both steps involving serious degradation in resolution. A further drawback to the color print mosaic is the limiting size of color photographic materials — usually a 40-by-40-inch maximum, which constrains most ERTS mosaics to 1:1,000,000 scale if more than two or three images are assembled.

All the problems of paper-print mosaics can be avoided or lessened by mosaicking with stable-base transparent film. Although film introduces a new set of problems, it allows the production of color-image maps of high geometric accuracy and suitable for lithography.

The New Jersey mosaic was prepared by first enlarging the separate bands of the three images directly to nominal 1:500,000 scale on continuous-tone, stable-base film, with little loss of resolution. Register between separate bands was maintained by using only simple enlargement with a constant enlarger setting. The band 5 images were then mosaicked by photomechanical contact printing to a new film using a set of exposure windows which precisely masked and bled together the adjoining images. The windows provide the critical diffraction trap that bleeds the butt joint of the images and eliminates the characteristic black or white line. The width of the trap depends on the film thickness and the exposure conditions on the contact printing frame.

The assembly of layers in the contact frame is shown in Figure 3a and a second exposure

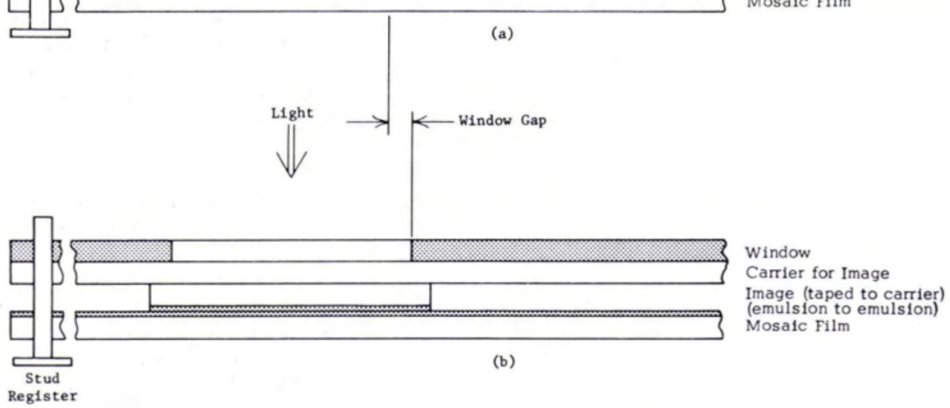

FIG. 3. Photomechanical film mosaicking.

for an adjoining image in 3b. Multiple nonadjacent images were exposed simultaneously, and successive exposures filled in the mosaic. The checkerboard arrangement of exposure windows and their images was completely prepared in advance and stud-registered. The adjacent image details were visually matched before exposure to ensure geometric continuity. The gray tone density was also matched from image to image.

After completion of the successive contact exposures from the band 5 film mosaic, the band 4 and 7 mosaics were assembled similarly. Usually the same windows were used. It is critical, however, to use the band 5 mosaic as a control base for positioning the separate images of other bands on the carrier sheets. Thus the image register maintained through enlargement will be preserved into the mosaic. After all three continuous-tone mosaics were completed, they were individually screened and prepared for lithography. High-resolution stable-base film was used throughout the process, and the separate bands were merged into a color image only during final printing. As a practical matter, several color proofs were prepared for quality control of the mosaicking process.

The New Jersey mosaic was also fitted with a 25,000-m UTM grid, as previously described. The final results on the printed map slightly exceeded NMAS, with an *rms* residual of 241 m.

After the first successful use of film mosaicking for color-image maps, the USGS EROS program boldly resolved to print an ERTS mosaic of Florida (Plate 1). This presented a new set of cartographic problems, not the least of which is the faulty foresight of the Florida explorers and settlers who established the state boundaries at odds with the ERTS orbital track. In contrast to the admirable clairvoyance of New Jersey colonists, Florida extends boomerang fashion across seven ERTS orbits. Further inspection showed that at least 16 nominal scenes contained part of Florida. One is over the Dry Tortugas, 75 miles west of Key West. Persistent cumulus cloud patterns appeared like scattered popcorn on many images, limiting the selection. Although southern Florida has a basically nonseasonal vegetation pattern, the northern panhandle has seasonal agriculture and deciduous forests to compound the difficulty of tone matching winter and summer images.

Although two or three ERTS images may be successfully enlarged and mosaicked into a map with only a scale factor, the assembly of groups of images demands a geodetic control network. The Florida mosaic was controlled photogrammetrically with a planimetric block adjustment to UTM coordinate values. UTM zones 16 and 17 separate the state midway across the panhandle at the 84° meridian. Due to width limitations of the printing press, the panhandle must be printed as an inset, and it was decided to control images in each zone separately.

The 14 images selected for eastern Florida and the four images covering the panhandle were enlarged to 1:1,000,000-scale on stable-base film. Photogrammetric pass points between images were selected on band 5 and stereoscopically drilled with a 50-μm mark on a point-transfer instrument (PUG). Ground control points were also identified and drilled. In a comparator the pass points, ground control, and the four register crosses imprinted by the NDPF were measured on each image. A least-squares adjustment was then performed to compute a conformal enlargement for each image constraining the image-to-image fit and simultaneously holding to ground control. The results were surprisingly good with a combined error of pass points and control of 105 m *rms*. The adjustment provided computed coordinate values for a 1:500,000-scale base sheet on which were plotted the ground control and the image register points. The pass points were not plotted. The register marks carried through the adjustment serve two purposes. First, they can be used as an enlargement templet for individual images. Second, they provide a positioning guide for the enlarged images on the carrier sheet during mosaicking.

The procedures developed on the New Jersey project for film mosaicking are being continued and refined. The complexity and handling difficulties increase by an order of magnitude if one mosaics 18 images from 12 different dates rather than three images from a single orbit. However the principle of contact exposure through adjoining matched windows is the same.

The collar for Florida is carefully designed and can serve as a guide for other State mosaics. The nominal scenes, the images used, and the index of existing 1:250,000-scale line maps are shown. The text explains some of the characteristics of ERTS and the image features.

A fitted UTM grid is also used on the Florida mosaic and the separate image-format maps. The grid was computed from ground control points using a revised computer program limited to a straight-line set of parallelograms that deviate almost undetectably from perfect squares. The estimated accuracy of well-defined points measured from the grid is 150 m, within NMAS, the first time such accuracy has been achieved on such a large ERTS mosaic.

All the individual image-format maps in Florida can be prepared as a byproduct of the mosaic. After each image is enlarged to control, an extra copy is prepared and screened. These copies are individually mounted in image-format collars with text, National Atlas inserts, and coordinates appropriate to the area. Because the image-format area is a standard size, the cartographic collars can be prepared independently of the images, and can be inserted and gridded when available.

One further experimental innovation is incorporated in the Florida ERTS mosaic and image-format maps. Many investigators have observed that, for pictorial purposes, bands 5 and 7 carry the most information. Band 4 generally lacks contrast between the major features observable with the limited MSS resolution. Band 6 is redundant to band 7 for many purposes. Although multispectral analysis and classification techniques may derive useful information from four or more bands, ERTS image maps portraying the shape and texture of the major themes of vegetation, water, and culture can be prepared using only bands 5 and 7.

Experiments have been conducted with some success to double-expose bands 5 and 7 on a single black-and-white film. However, this generally creates the effect of black-and-white infrared film. More desirable is a color rendition that incorporates the proved interpretability of color-infrared film. This can be achieved by printing band 5 twice, once with the usual magenta ink and the second time with the yellow ink normally used for band 4. Band 7 is printed with the usual cyan ink.

The screen angles and halftone percentages are different for each plate. The result is an image which closely resembles the usual false-color rendition. Considerable time is saved in mosaic preparation if only two bands are assembled in register rather than three. Although it may sound heretical to abandon multispectral information from band 4, the pictorial loss in most instances is undetectable. Whether this two-band, three-color printing process will be continued on other ERTS maps in other geographic areas depends upon the results of further research and public acceptance.

Conclusions

USGS has conducted research and development to lithograph color image maps using MSS images from ERTS. These include the Lake Tahoe Area precision image, the Upper Chesapeake Bay image-format map, the New Jersey mosaic, and the Florida project which includes a state mosaic and image-format maps. All have followed the general representation of color-infrared film. Lake Tahoe was at 1:1,000,000-scale, and the others have been at the more effective scale of 1:500,000.

Several accomplishments may be directly cited:

- Definition and computation of a regular worldwide series of nominal ERTS scenes that can be used for indexing.
- Development of an image-format map series using named and numbered nominal scenes as a base.
- Use of photomechanical film mosaicking as a mapping technique.
- Use of a fitted cartographic grid to improve geometric accuracy and turn images into maps.
- Design of complete cartographic collars specifically for ERTS maps.
- Use of computational photogrammetry to control the scale and image match of large mosaics.
- Use of bands 5 and 7 to provide a two-band, three-color rendition similar to that of color-infrared film.

It is interesting to note that none of these developments were specifically the topic of any ERTS-1 investigation with NASA. Rather they have all resulted from the serendipity of events since the launch of ERTS-1. They represent the progressive results of one agency developing new techniques to use a new tool. This in no way detracts from defined ERTS experiments but illustrates both the difficulty of stating research results in advance and the need for other agencies to fashion their own applications.

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PLATE 1. ERTS-1 satellite image mosaic of Florida.

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