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Restored Pictures of Ganymede, Moon of Jupiter

Digital restoration of two space pictures of Ganymede has revealed some interesting surface features.

B. Roy Frieden and William Swindell

Ganymede is the largest moon of Jupiter, having a diameter of about 5000 km. Because earth-based telescopes can barely resolve it, the details of Ganymede's surface are largely unknown. Other, nonvisual evidence has led to the belief that its surface is very rough, largely composed of rocky or metallic material embedded in ice (*1*). The detailed pictures presented here provide a body of visual information on the surface makeup of Ganymede.

During its mission to Jupiter, the Pioneer 10 spacecraft acquired two pictures of Ganymede (*2*), which provided a much improved view of its surface. The pictures were obtained with two different color filters, one in red (5950 to 7200 Å) and one in blue (3900 to 5000 Å). Unfortunately, these pictures are quite blurred because of the small scale of details on Ganymede relative to the size of the image blur spot (the total instrument response function).

We report here the results of an attempt to restore the pictures—that is, to remove the blur due to the instrument response function. Such removal is at least theoretically possible, because the instrument response function is deterministic, and largely known.

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Let $s(x,y)$ represent the instrument response function, with x,y the usual space coordinates. Mathematically, the restoration problem consists in inverting the imaging equation

$$i(x_m,y_n) = \iint_{\text{scene}} dx'dy' O(x',y') \times s(x_m - x', y_n - y') \qquad (1)$$
$$m,n = 1,2,\ldots,M$$

for the unknown $O(x',y')$, the "restoration." The irradiance image data $i(x_m,y_n)$ and response function $s(x,y)$ are assumed known, from measurements, and hence contain noise. Such noise is the chief impediment to estimating $O(x',y')$.

Three factors aided in making such restoration practicable. First, the irradiance image is a linear function of the image data; hence, there are no problems of estimating the irradiance image such as occur when the image is photographic.

Second, and most important, the image was sampled at a sufficiently fine subdivision to allow some degree of enhancement. There were about 28 sampled image values within the central core of the two-dimensional instrument response function.

Third, the instrument response function is very nearly separable. That is, if $s(x,y)$ represents the general response function, with x,y the usual space coordinates, in our case

$$s(x,y) \simeq s_1(x)s_2(y) \qquad (2)$$

Functions s_1 and s_2 are the x- and y-component marginal distributions of s. Although Eq. 2 is an approximation, the maximum discrepancy between the left- and right-hand sides is about 2 percent of the central maximum in s. Figure 1 shows the marginal imaging kernels s_1 and s_2.

Separability is important because it permits use of a restoration procedure—the maximum entropy algorithm—whose output is constrained to be positive (or zero) everywhere (*3*). The general two-dimensional case would otherwise require too much computer time. Because of separability, the two-dimensional image may be restored as a sequence of one-dimensional, or line, restorations. These may be implemented with enough speed to permit the positive constraint to be enforced on the moderate-sized Ganymede pictures discussed below.

One negative aspect of the problem was the occasional existence of artifacts in the image data. Even worse, the artifacts were systematic—that is, highly correlated—and hence indistinguishable from true detail. We discuss below the steps we took to minimize this problem.

The images were restored in two different ways: by conventional linear filtering and by the maximum entropy algorithm cited above. To the best of our knowledge, the latter is the first published use of this kind of algorithm on real (nonsimulated), moderately extended image data.

The linear restoring algorithm was of the type used by Nathan (*4*)—inverse filtering, with a maximum permitted boost in amplitude specified by the user. Phase was always fully corrected. All operations on the image data were in direct (compared to frequency) space. Hence, the image was restored by convolution with a function whose Fourier transform is the upper-bounded, inverse filter. We tried maximum boosts of 2, 4, 5, and 10 before settling on 2 as the most reliable.

Image Geometry and Sampling Rates

The images were two arrays of data, each 33 points across (y direction) by 23 points down (x direction). The data spacings were 0.33 mrad in x and 0.195 mrad in y.

The restored images are constructed on a finer mesh. For the maximum entropy outputs (*5*), these are 65 points across by 45 points down, with point spacings of 0.165 mrad in x and 0.0975 mrad in y. The corresponding array size for the linear restorations was 65 by 67. The existence of a finer mesh potentially permits higher resolution in the output. All restoring methods were carried through by first restoring in x—that is, down each column—and then in y, across each row.

For effective data processing, it is necessary that the sampling rate in each coordinate direction be sufficiently high. As a rule of thumb, five sampling points per direction, within the central core of the instrument response function, are required. In our case, the situation is as in Fig. 1, where sampling positions of the Ganymede data are marked along each instrument response curve. Because there are four sampling points in x within the instrument response function s_1 and seven in y within s_2, we see that sampling was somewhat deficient in x but more than adequate in y. We can therefore expect in the restorations more accuracy in the y direction (horizontal) than in the x direction.

Reliability of Data

When the Pioneer 10 optics were tested before the Jupiter mission, inaccuracies in the image data were small. For the level of brightness in Ganymede, maximum image errors of about 7 percent were found, with a root-mean-square error of about 2 percent. This is an adequate accuracy for image restoration.

However, once the spacecraft was in flight, it became apparent that the red channel occasionally records substantial artifact information. When present, this appears as additive noise in the form of wavy, parallel lines (somewhat resembling a fingerprint). A particular red image may suffer this problem over all, or part, of it. Pictures of Jupiter taken immediately before and after those of Ganymede showed the defect, which implies that it is present in the Ganymede photos.

Fortunately, the blue channel suffers little, if any, error of this kind, and presumably still provides preflight performance. This gives a check on the red information and ultimately a measure of reliability for it, as follows.

Ganymede is most often modeled as having little atmosphere and consisting mostly of ice and rock. Such features would have little coloration. Hence, where the red channel lacks artifacts, the information it provides should be nearly proportional to the blue channel information—that is, the two sets of data should have a very high correlation coefficient. Conversely, when red artifacts are present, the two data sets should not correlate well.

This allowed us to establish a measure of reliability for different portions of the red Ganymede image. We first computed the cross-correlation coefficient between the entire red and blue images. This was .73, which indicates the presence of some artifacts (*6*). Next, we computed the correlation coefficients for corresponding quadrants of the image, with the intersection point at the center of the disk.

The results were most informative. As shown in Fig. 2, the upper left quadrant has a red-blue correlation of .35, the lower left .56, the lower-right .73, and the upper right .92. We use these as measures of our confidence in the red data over those regions.

Restoring procedures cannot distinguish true image details from systematic artifacts (the type present) and will equally enhance both. Therefore, given the above correlation figures, we should, for example, be skeptical of restorations of the upper left quadrant of the red Ganymede image, assuming the hypothesis of little coloration to be correct. As mentioned before (*6*), Pioneer 11 data seem to corroborate this hypothesis.

Image Data

In the images shown here, the local central meridian is approximately 103° and runs approximately from the upper left to the lower right. The subspacecraft latitude is −18°. The terminator is on the right-hand side of the pictures and the solar phase angle is 37°.

Figure 3a shows the red channel image of Ganymede and Fig. 3b the blue channel image. The minimum resolvable length in these images is about 390 km (*2*) (on a scale where disk diameter is 5000 km).

To enhance the visual appearance of these pictures, the data were stretched out geometrically by a factor of about 8 to 1 and linearly interpolated. Also, the otherwise weak internal features were accentuated by use of a photographic gamma exceeding unity and of high exposure.

With these visual aids, a few features of interest (see pointers, Fig. 3a), which are common to the two images, become apparent. First, there is a dark, caplike region on the terminator in the upper right quadrant of the disk, with a complementary bright region in the lower left quadrant. There is a small bright feature within the lower right quadrant, and a large dark area in the upper left quadrant. These gross features became more detailed, and interesting, in the restored pictures below.

The blue image in Fig. 3b is of further interest in that it has some more pronounced circular features (see pointers). In view of the appreciable diameter of Ganymede (about 5000 km) these are quite large. That these are maria or ice fields seems a plausible working hypothesis.

Restoring Algorithms

All data processing was done with a Control Data Corp. 6400 computer. Computer time for each maximum entropy picture was about 30 seconds. To the best of our knowledge, this is a much shorter computer time for an image the size of Ganymede than has been required in any previous use of the maximum entropy algorithm. For example, Wernecke (*7*) reported a time requirement on the order of an hour for a 21 by 21 array of data.

All maximum entropy restorations were formed with a sharpness factor (*3*) $\rho = 5$, which yielded a modest level of enhancement. In this situation, a negligible level of artifact details is created by the restoring technique itself. The exception is at the periphery of the disk, where the familiar Gibbs oscillation phenomenon arises because of the abrupt change in intensity. These oscillations are, however, easily recognized and suppressed. At higher test values of ρ than 5, some artifacts occur, somewhat resembling orthogonal sets of lines at 45° and 135°. However, these values of ρ were not used in the restorations reported below.

All linear restorations were of the type previously described, and were formed using a boost factor of 2. With this choice of boost, there was also a negligible level of restoration-induced artifact. Artifacts occurred for higher levels of boost, and these also took the form described above. We used the linear restoration method (i) to obtain an independent check of the reliability of the maximum entropy algorithm, and (ii) to see which restoring technique gives a higher-quality output when both are done at the same (negligible) artifact level. Previous tests (*3, 7*) have shown maximum entropy to yield better results. However, these were for pointlike objects, such as star fields, which significantly differ from an extended object such as Ganymede.

Restorations

Figure 4 shows the red channel image, its restoration by maximum entropy, and its restoration by linear filtering. The restorations have been geometrically stretched to coincide in size with the image data.

Let us now examine the maximum entropy restoration, Fig. 4b. Visually, this has a much higher level of detail than Fig. 4a. The finest resolution length in Fig. 4b is about 190 km, compared to 390 km in Fig. 4a.

It is informative to observe the enhanced versions of the image features previously described (see pointers, Figs. 3a and 4b). First, the caplike region at the upper right-hand edge in Figs. 3a and 4a is more sharply delineated in Fig. 4b. This is consistent with the way a crater, or other large hole, would appear on the dark limb side. Beneath it in Fig. 4b is an elliptical, darkened region that resembles a large, shallow crater, as one would appear within a generally darkened limb region and in an oblique view. This has a faint counterpart in the image, Fig. 4a.

Nearby in Fig. 4b are features with a craterlike appearance. Finally, the small bright feature within the lower right quadrant of Fig. 4a is more sharply delineated and smaller in Fig. 4b, where it now appears as the center of a large, scallop-shaped bright arc. Notice that this arc was previously seen in the blue image, Fig. 3b. Thus, the red restoration and the blue image confirm one another, and this is important because the two channels are independent sources of information. The bright arc must be a real feature. Regarding overall confirmation of results, we may note that all features discussed so far lie in the upper right and lower right quadrants, regions of high data reliability according to Fig. 2.

Continuing the comparison of Fig. 4a and Fig. 4b, the generally dark region of the upper left-hand quadrant of Fig. 4a is restored in Fig. 4b as a series of bands, running approximately from upper left to lower right. Figure 2 leads us to suspect that this feature is merely an enhancement of the artifacts in the red data. But there are features within the bands that are probably not artifacts, because these will be seen to correlate well from blue to red channels. However, the bands themselves will not, which lessens their credibility.

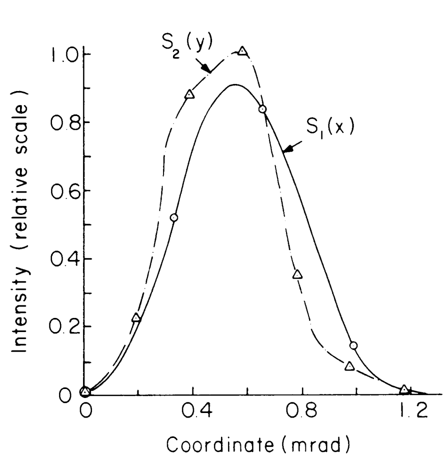
We next examine the linear restoration, Fig. 4c. Comparing it with Fig. 4b, we observe a resemblance between grosser details of the two. That is, except for a lower state of resolution in Fig. 4c, every feature in it is also present in Fig. 4b. However, the reverse is not true. Figure 4b provides a great deal more visual information than does Fig. 4c, in the form of (i) sharper edge gradients for the details they share in common and (ii) details of finer structure lying between these. This comparison, we believe, shows the improved resolution obtained with the maximum entropy technique compared to linear techniques.

A detail of further interest in Fig. 4, b and c, is the conspicuous bright band that appears to encircle the dark cap at the top (see pointer). According to Fig. 2, this is probably a real feature. As a working hypothesis, we suggest that the feature is a circular ridge, perhaps of ice. Large, circular, bright features seem to be common on Ganymede (see previous discussions of Figs. 3b and 4b).

The blue channel image data, maximum entropy restoration, and linear restoration are shown, respectively, in Fig. 5, a through c. Because not much coloration effect is expected for Ganymede, our original interest in the blue results was in the extent to which they agree with and verify the red results. There is good agreement in the following features of Figs. 4b and 5b, or 4c and 5c: the dark cap; the small white feature and its bright, encircling arc; and the white region at the lower left edge.

However, Fig. 5, b and c, contain something new, not found in Fig. 4. In the upper left-hand quadrant of Fig. 5, b and c, there are three round details (pointers) that very much resemble maria. If so, the maria are very large. Figure 5b also shows some structure within the topmost round feature, which makes it reminiscent of certain lunar maria.

In retrospect, these apparent maria can also be seen, albeit very faintly and greatly



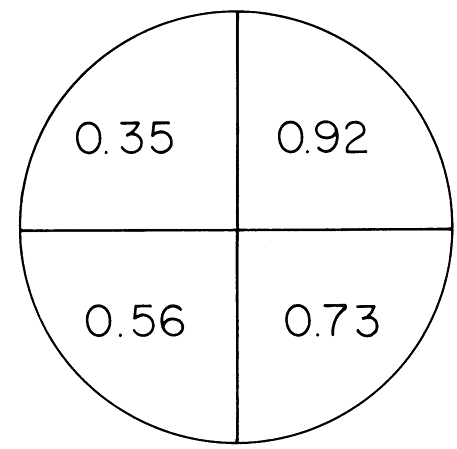


Fig. 1 (left). Marginal instrument response functions $s_1(x)$, $s_2(y)$ for the overall imaging system of Pioneer 10. Experimental data establishing these curves are spaced at 0.05 mrad. Points indicated on each curve show the sampling spacing, in each coordinate direction, for the Ganymede image data. Fig. 2 (right). Red-blue correlation coefficient for each quadrant of the input data arrays. The extent to which these data correlate offers a measure of confidence for the red data.

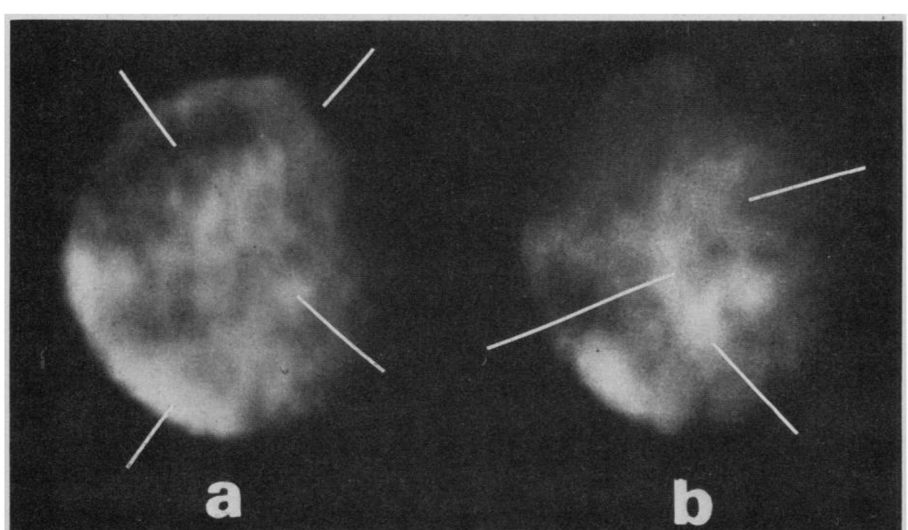


Fig. 3. Ganymede image data: (a) red channel, (b) blue channel. As a visual aid, the data have been developed with high photographic gamma, geometrically stretched, and linearly interpolated. The white pointers indicate key features that will show some interesting structure in the restorations to follow.

blurred, in the red and blue images (Figs. 3a, 3b, 4a, and 5a). Comparisons of these images with Fig. 5b illustrates the power of restoring methods to render marginally visible details strongly visible, and with additional detail. In view of the clarity with which Fig. 5b shows the three apparent maria, it is rather surprising that others are not seen elsewhere in the disk. Perhaps this implies that such maria are rare on Ganymede.

The linear restoration, Fig. 5c, also shows the maria, but with less resolution. Furthermore, it does not restore the internal detail of the topmost one, shown in Fig. 5b. This again illustrates the resolution advantage enjoyed by the maximum entropy technique over linear methods, when all operate at the same (negligible) level of artifact detail.

Color Composites

Color pictures of Ganymede may be formed by superimposing corresponding red and blue images, or corresponding restorations. However, for a proper visual color effect three primary colors are needed. In our case the third color must be added artificially, somehow based on the two available colors (red and blue). The method chosen was arbitrary, but works well when applied to Jupiter. We created an artificial green intensity at each pixel by forming a linear combination of the red and blue values there. By this method a pure green could not be formed, nor could a pure purple. But, for Jupiter at least, these hues do not exist in significant amounts, so the method works well.

The applicability of this method for Ganymede is, however, more speculative. It is not known a priori what distribution of hues Ganymede contains, so that green or purple regions cannot be ruled out. However, its overall hue may be observed from the earth, and this information may be used as input to the coloration scheme. The coefficients that weight the red and blue contributions may be chosen so that the acquired color image has the same overall hue as in an earth-based view. In this way, the top image on the cover was formed from the red and blue image data of Fig. 3. (Note that this has an overly enhanced green component due to an oversight in darkroom procedures.)

There is another benefit, aside from obtaining a color photograph, to be gained by such a superposition. It may also give us a means of increasing the signal-to-noise ra-

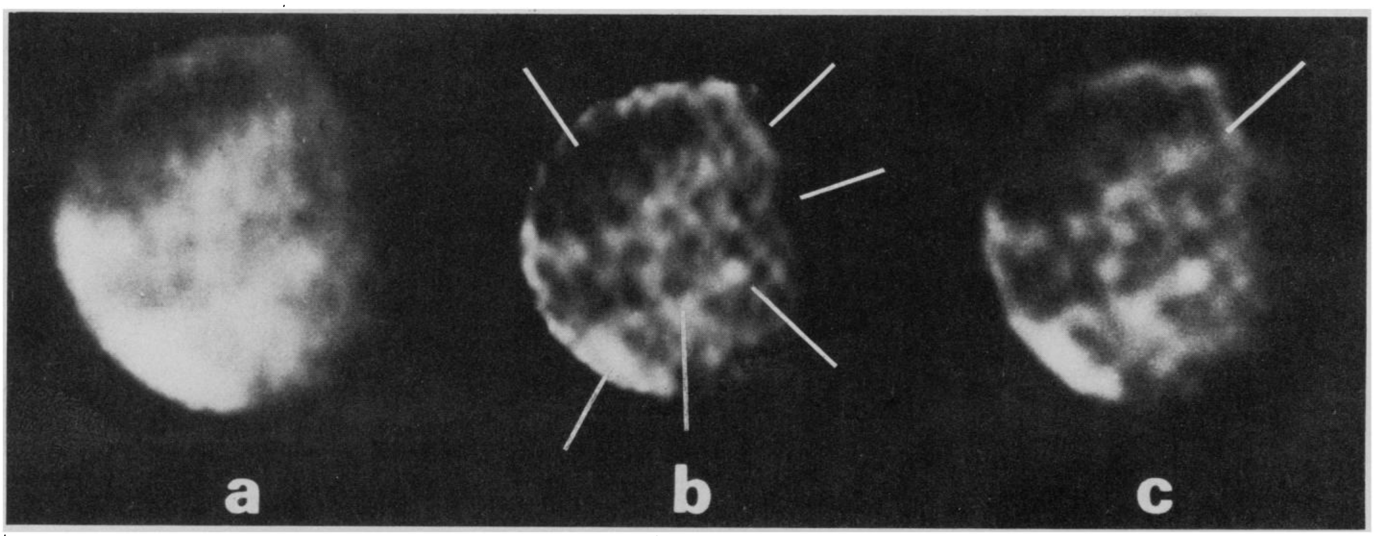


Fig. 4. Red channel image (a) and restorations by maximum entropy (b) and linear convolution (c). The pointers indicate enhanced versions of the key features pointed out in Fig. 3a.

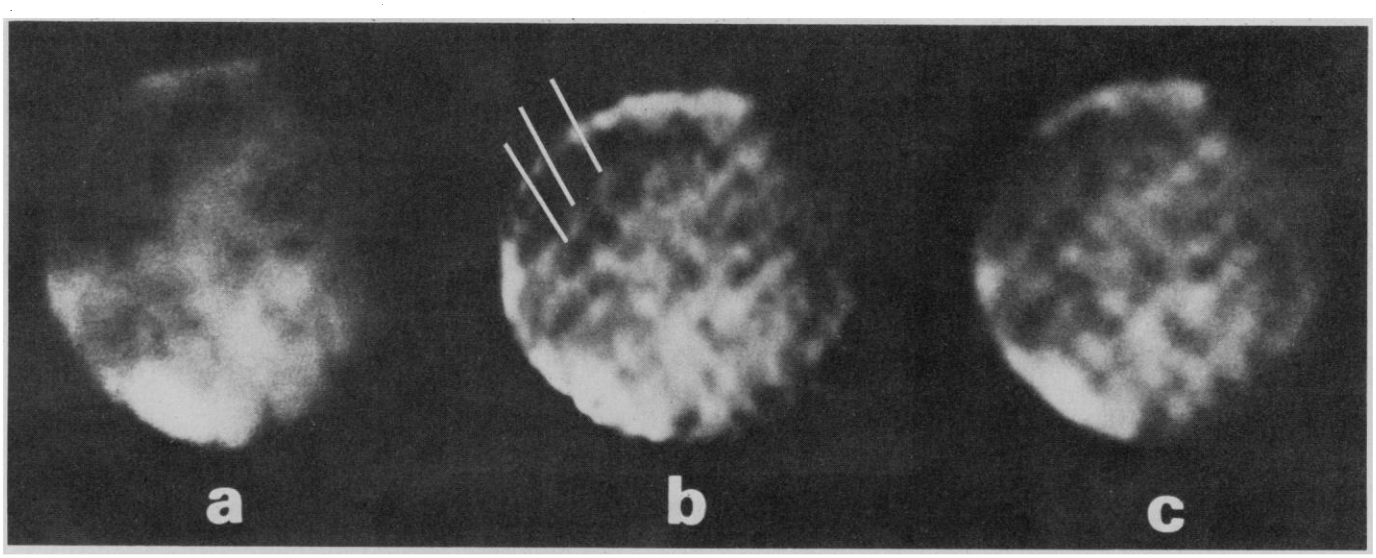


Fig. 5. Blue channel image (a) and restorations by maximum entropy (b) and linear convolution (c). The pointers indicate three mare-like features. The top one actually appears to show some internal structure. The bottom mare seems to intrude into the middle one, which is reminiscent of certain lunar maria.

tio across the picture. Since Ganymede is expected to have weak coloration (*1*) the red and blue images (or corresponding restorations in these colors) should strongly correlate spatially. So, therefore, should the artificial green with both the red and the blue. Now, in a composite, correlated features come through strongly, while uncorrelated or weakly correlated features do not. By the hypothesis of weak color effect, the latter should tend to be artifacts anyhow. The upshot, then, is that the ratio of true to false details in the Ganymede pictures should be enhanced by the color superposition. A corollary, however, is that any strong color (departure from the gray range) is suspect.

Color versions of the restorations were produced in a similar manner. At each pixel, an amount of green was generated equal to the arithmetic average of the red and blue intensities there. Before this step, the red and blue pictures were equalized in total light intensity. The effect of the green addition, then, is to produce an equal-energy white color where red and blue are equal. The philosophy here is that, if red and blue are equal, and nothing is known about green, the simplest assumption to make about green is that it equals both the red and the blue value, thereby producing a net color that is a shade of gray (the most unbiased or conservative choice of "color" in these circumstances).

In this manner, the linear restorations in Figs. 4c and 5c were used to produce the color output in the middle image on the cover; and the maximum entropy restorations in Figs. 4b and 5b were used to produce the color output in the bottom image. As before, the maximum entropy picture exhibits more detail than does the linear one.

Summary

Restored pictures of Ganymede have been produced that have some identifiably reliable features and some identifiable artifacts. The latter arise from artifacts in parts of the red image data. Among the presumably reliable features are some mare-like objects (perhaps with some internal structure), and a few rather large, bright rings. Whether the latter are ice, or arise from near-specular reflection from smooth surface features, is left for future investigation.

One of the restoring methods used, maximum entropy, has been shown to be applicable to moderately extended images. In view of its short time requirements (30 seconds per picture), the method should be applicable to moderately larger images, for example with twice the given number of data points.

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5. If the output restoration is denoted $\hat{o}(x,y)$, its entropy H is defined as

$$H = -\int\int \hat{o}(x,y)\ln\hat{o}(x,y)dxdy$$

This H is maximized, subject to the input image data as constraints.
6. An identical calculation for Pioneer 11 data on Ganymede gave a correlation coefficient of .91. By comparison, Pioneer 11 data suffer little, if any, artifact detail. (However, they were sampled more coarsely than the Pioneer 10 data, and so are less appropriate to restore.)
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8. The authors gratefully acknowledge the assistance provided by members of the Pioneer Imagery Photo-Polarimeter team of the University of Arizona, and personnel of the Pioneer Project Office of NASA-Ames Research Center In addition, we thank D. Wells of Kitt Peak National Observatory for his strong encouragement and for permitting access to the Comtal display equipment at his facility. This work was supported in part by NASA contract NAS2-6265 and by Air Force contract F33659-72-C-0605.

NEWS AND COMMENT

Blind Medical Student: Overcoming Preconceptions

David Hartman probably would have done very well for himself anyway, but, owing to a combination of circumstances, people, and his own character, he is emerging as perhaps a very significant individual.

Hartman, 26, is the first blind person to have been admitted to an American medical school in almost a century. He is now a senior at Temple University School of Medicine in Philadelphia and will graduate in May. He has completed, with only minor deviations, all the courses required of his sighted colleagues. He plans to be a psychiatrist, with special emphasis on the physical and psychological rehabilitation of handicapped people.

Doctors who continue their practice after becoming blind are not unknown; Hartman even knows of a couple who continued their medical training after losing their sight. But starting from scratch without any vision is another matter, and there are few medical schools that will even consider letting in such a student. The last time it happened was reportedly in 1878, when Robert H. Babcock entered Chicago Medical College. Babcock learned anatomy by touch and went on to write books about heart and lung diseases.

While Hartman's success has helped fracture some preconceptions about the limitations of the blind, it by no means presages a deluge of blind entrants to medical school. "David is a unique person," says M. Prince Brigham, assistant dean for admissions at Temple. "For every David Hartman there are thousands [of talented blind people] who would find medical school so utterly and maddeningly frustrating" they would never make it. "He has . . . ego strength—a self-awareness sufficient to allow him to withstand some of the disappointments he faces." It all boils down, says Brigham, to his being "extremely mature."

Hartman says that some people to whom he reveals his calling conjure up visions of carnage in the operating room—which would seem to reflect a belief that anyone who is blind would have to be some sort of magician or superman to keep up. But Hartman, as he himself insists, is no genius. He is, however, well organized, realistic, determined, and intelligent. He has a kind and thoughtful presence, quite doctorly, and an appealing chuckle that gives one the impression he feels secure in his control over his life.

He has a fairly well developed philosophy, one of the major tenets of which is that everyone is handicapped in some way, usually less obviously so but often no less. Think, for example, "of a guy who just can't relate to people going into psychiatry."