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THREE DIMENSIONAL CHARACTERISTIC OF THE SHROUD IMAGE

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Abstract

The frontal image on the Shroud of Turin is shown to be consistent with a body shape covered with a naturally draping cloth and which can be derived from a single, global mapping function relating image shading with distance between these two surfaces. The visible image on the Shroud is not the work of an artist in an eye/brain/hand coordination sense, nor does it appear to be the result of direct contact only, diffusion, radiation from a body shape or engraving, dabbing powder on a bas relief, or electrostatic imaging. The visible image on the Shroud is probably not the result of a hot bas-relief impressed into cloth, but such a mechanism might be able to account for the Shroud image's distance correlation, resolution, and chemical structure; it does not simultaneously account for the image residing on one side of the Shroud, low contrast of the Shroud image, or lateral distortions in the Shroud image consistent with a draping cloth over a body shape.

I. INTRODUCTION

In Turin, Italy there exists a 14 foot 3 inch linen cloth known as the Shroud of Turin. This cloth contains visible discolorations of the apparent frontal and dorsal images of a human male form (Figure 1). The image appears to be that of a crucifixion victim who has been whipped, knifed in his right side, and physically abused. These characteristics, reminiscent of what the Gospels report happened to Jesus, have led some to hypothesize that the "Man of the Shroud" is Jesus while others still remain cautious, awaiting in some instances a radiocarbon date of the Shroud. In this paper, we consider the Shroud image from a point of view that is independent of the identification of the Man of the Shroud and accordingly all conclusions reached are independent of whether or not the Shroud is the actual burial cloth of Jesus. The general layout of the frontal and dorsal images can be interpreted as having been produced from a body enveloped between folded halves of the Shroud. It is in this sense that the cloth can be interpreted as a shroud. However, correct scientific inquiry regarding the nature of the Shroud image must not exclude the possibility that the image was the work of an artist, possibly made to look like the burial shroud of Jesus. As an art form, the image might have been produced by simple eye/brain/hand coordination (like a painting) or by some physical mechanism (i.e., chemical transfer from a human corpse or statue.)

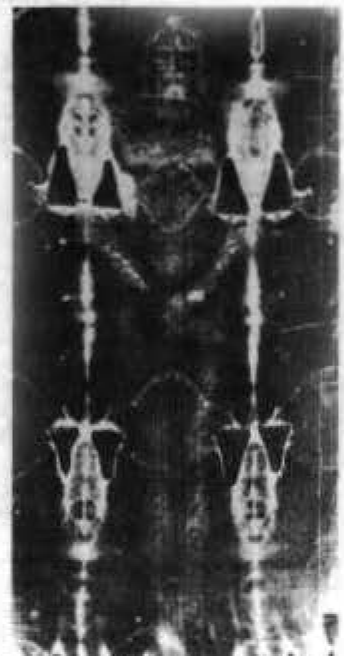

Figure 1. Frontal Shroud Image. Vernon Miller,1978

In this paper, we discuss the Shroud image with respect to its shading structure. For discussions of the Shroud image relative to its chemical properties as well as aspects of the Shroud outside the scope of this paper, we refer the reader to other literature (Refs. 1-4). Our discussion consists of two parts: first, we determine the type of shading structure contained in the Shroud image and second, we discuss various hypotheses with respect to the type of shading structure determined. Our analysis of the first part will presume nothing of the chemical nature of the Shroud image and accordingly, this discussion will be independent of image chemistry. In the second section, however, we discuss chemical considerations where appropriate so as to integrate this paper with other studies.

II. CHARACTERIZATION OF SHADING STRUCTURE

A. Discussion. Gilbert and Gilbert (Ref. 5) and Pellicori (Ref. 6) have published spectral reflectometer curves taken directly from the Shroud image. As a general rule, curves from

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various body image locations show similar shape but vary only in their offsets in reflectivity magnitude. At 550 nm, midpoint of visual response, the minimum absolute reflectivity (at nose) is approximately 24%, cloth background 30%, and new linen 58%. Image reflectivities at 680 nm (red) and 440 nm (blue) are in the approximate ratio of 2.6:1. Thus, the image appears on a yellowed linen cloth as a faint, yellow-brown discoloration, with shading intensity being the only optical characteristic which varies from point to point so as to produce the pattern of a human form.

Given that the discolorations on the Shroud describe a human form, it is natural to ask if image shading, I, might be associated with some property, P(x,y), of a human body via a relation

$$I(x',y') = f[P(x,y)] \qquad (1)$$

where (x',y') are coordinates of some image point on the Shroud and (x,y) the coordinates of the associated image feature on the body shape. It is conceivable that no such relation exists at all, particularly if the image were the work of an artist, but if one could be established, then we might obtain some insight regarding the process which formed the image. Conceivably, there are many properties of a human body which could be functionally related to the shading structure of the Shroud image. Some may be incidental properties of the body surface such as temperature, reflectivity, perspiration density, roughness, etc. Others may be related to the geometry of the body surface. For example, if z=u(x,y) describes that surface, then the geometric quantities z, gradient z, and higher order derivatives of z could conceivably be mapped into shading as well. Thus, if we are to properly study the image on the Shroud, we must identify the type of shading correlation present in its shading structure, and analyze various image formation hypotheses in light of this determination.

Of the many possible parameters which might correlate with image shading, we chose to examine first the parameter of cloth-body distance, d, based on a photographic study of the Shroud by Vignon in 1902 (Ref. 7). Vignon noted that the darkest parts of the image seemed to correspond with the high relief parts of a body shape where cloth contact could be expected. We therefore, decided to examine the shading of the Shroud image for a possible correlation with expected cloth-body distances.

B. Small Sample Correlation Technique. Our procedure for measuring the degree of correlation between image shading and cloth-body distance involved first measuring the transmittance of a black and white transparency of the face taken of the Shroud in 1978 (Ref. 8) by a microdensitometer. We chose to sample 13 image locations: tip of nose, edges of nose, cheek, eyes, eye sockets, bridge of nose, lips, mustache, and forehead. The limited number of sample measurements was determined by the small number of image features which we felt could be accurately identified.

Next, we measured cloth-body distance by draping a linen model of the Shroud, hand woven so as to correspond with the herringbone weave and thickness of the Shroud (Ref. 9), over a beared volunteer subject. Side photographs were made with the cloth in place and then after immediately being removed. By superimposing these photographs and using contour gadges (taking care not to deform the cloth) we determined cloth body distances. We note that these measurements do not provide us exactly with the cloth-body distances appropriate for the Shroud image since the subject and cloth drape are at best approximation. Thus, some intrinsic error can be expected to be present.

We then plotted these data of transmittance and cloth-body distance and determined a linear regression line shown in (Figure 2). As a measure of the degree of correlation we calculated the coefficient of determination, r^2, (correlation coefficient squared) given by (Ref. 10)

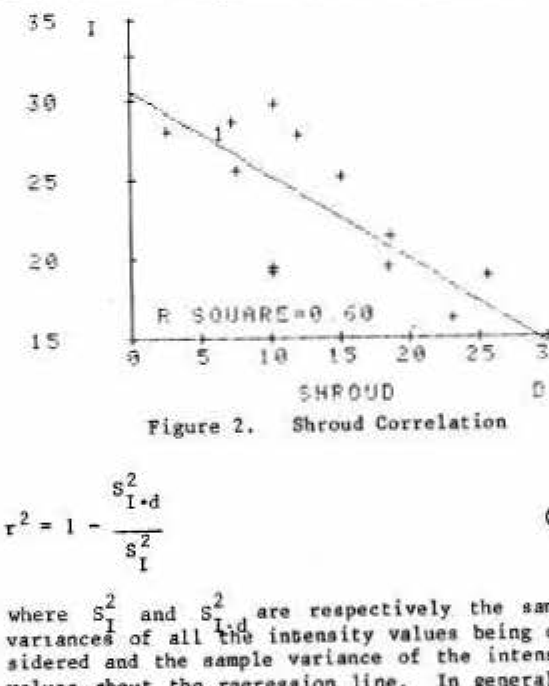

Figure 2. Shroud Correlation

$$r^2 = 1 - \frac{S^2_{I\cdot d}}{S^2_I} \qquad (2)$$

where S^2_I and $S^2_{I\cdot d}$ are respectively the sample variances of all the intensity values being considered and the sample variance of the intensity values about the regression line. In general r^2 is calculated from a finite number of data points, n, and as such only approximates the true coefficient of determination, $\rho^2 = \lim_{n\to\infty} r^2$ of the entire set of data pairs (I,d).

The measured coefficient of determination, r^2, was 0.60 for the 13 data points; at the 95% confidence level, this result implies that the actual coefficient of determination, ρ^2, lies between 0.20 and 0.83 (Ref. 11). Though the range is quite large owing to the small number of data points available, some observations can nevertheless be made. First, the null hypothesis that ρ^2 = 0 is excluded by these data with 95% confidence, indicating that some correlation with image shading and cloth-body distance is present in the Shroud image as Vignon suggested. Second, if we assume that the image was produced by the cloth draping over a body shape, which is consistent with the data, then we can estimate the effective range of discoloration effects on the Shroud. We define this range as that distance at which the regression line intersects the average cloth background intensity. According to this definition, we calculate the range to be 3.7 cm.

The reliability in the measurement of ρ^2 could be increased if more data points were sampled. We can estimate the number, n, of data points required by the approximate formula derived from equations in Reference 12:

$$n = \frac{16(1-\rho^2)^2}{\rho^2[d(\rho^2)/\rho^2]^2} \qquad (3)$$

If we require $d(\rho^2)/\rho^2$ to be 5% and use the mean value of $\rho^2 \approx r^2$ = 60%, we calculate the number of data points required to be 1700. If however, ρ^2 is higher than our 60% estimation, then the required number of samplings for 5% accuracy would be less. The value of 1700 is prohibitive by the manual sampling technique discussed above, but may be possible via some automated sampling algorithm. The main difficulty, however, in constructing such an algorithm is in being able to accurately register points in the image (x',y') with associated points on a reference face (x,y) to the accuracy of the sampling pixel size involved.

C. Relief Image Technique. Although we have not as yet developed an adequate large number sampling algorithm, we have studied the Shroud image with another technique that allows visual estimation of how well image shading correlates with distance. The technique involves scanning a given image with an Interpretation Systems VP-8 Image Analyzer (Ref. 13), an analogue system that displays image shading as proportionate degrees of spatial relief on a CRT screen in real time. This instrument has also been used as an image processing device by other investigators (Refs. 14-16). We measured the resolution of the VP-8 to be equivalent to roughly 1300 pixels over a facial surface, nearly the number required for a 5% measurement of ρ^2. This instrument is ideally suited for determining whether a given image contains distance information because it converts image shading into relief or distance which is the quantity we are trying to correlate.

As an example of how the VP-8 shows a correlation of image shading with distance, consider the images of Figure (3). The image in Figure (3-A) is a normal black and white photograph of a plaster face and is therefore an "albedo" map of how light was reflected off the face into the camera. The image in Figure (3-B), however, has a shading structure which corresponds not to albedo, but to the geometrical structure of the plaster face. This image was produced by uniformly coating the face with phosphorescent paint and, when optically charged, this face was photographed through a light attenuating liquid in which it was submerged. The result was an image whose shading depended upon how far light propagated through the attenuating liquid, that is, upon distance from the face to the flat reference surface of the liquid.

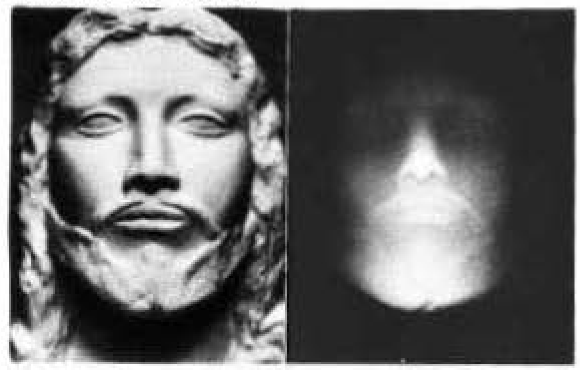

Figure 3. A. Albedo Face. B. Phosphorescent Face.

Both images were derived from the same facial surface, but only the one of Figure (3-B) has a shading structure that correlates directly with distance. Figure (4) shows image intensity versus distance plots and associated linear regression lines generated by the same procedure and sampling locations discussed previously for the Shroud image. r^2 for each image is: abledo - 0.17, and phosphorescent - 0.98. As for the Shroud image at the 95% confidence level, the albedo image has a large uncertainty (ρ^2 between 0.00 and 0.52; while for the phosphorescent face, r^2 is sufficiently large that, even for 13 sample measurements, the range of ρ^2 lies between 0.98 and 1.00 (Ref. 11).

Figure (5) shows the VP-8 image intensity surfaces corresponding to the two images of Figure (3). It is obvious that only the VP-8 relief surface corresponding to the distance encoded image of Figure (3-B) (phosphorescent) accurately models the geometry of a facial shape. It is noteworthy that the magnitude of r^2 as measured above for these images seems to parallel the degree of closeness that each image approximates a facial shape.

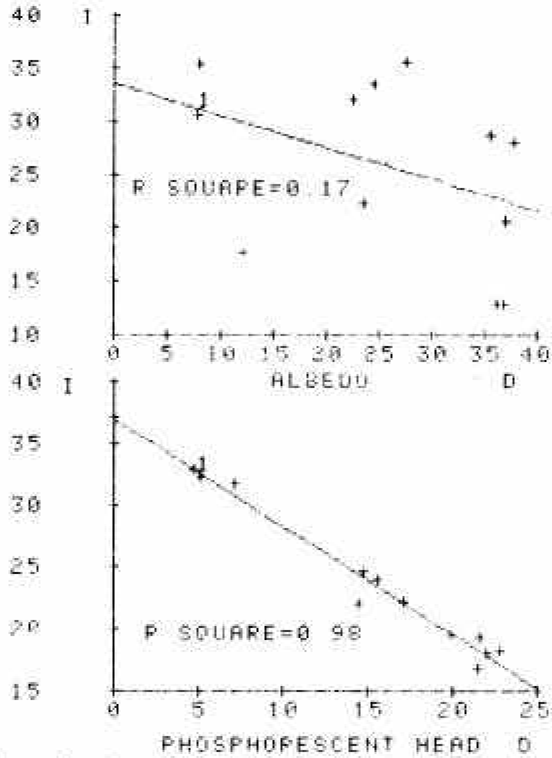

Figure 4. A. Albedo Correlation. B. Phosphorescent Correlation.

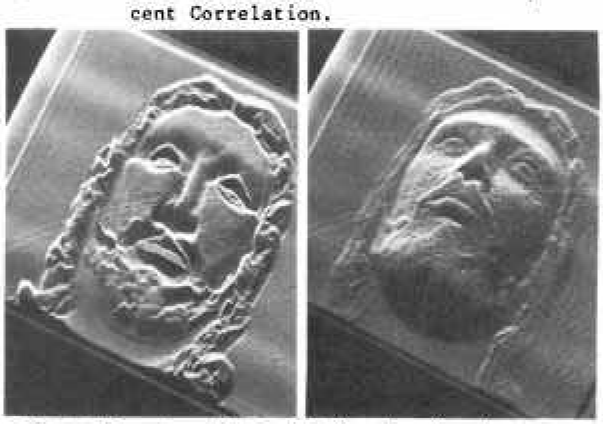

Figure 5. A. Albedo VP-8. B. Phosphorescent VP-8.

Thus, the VP-8 system is capable of providing imagery from which degree of distance correlation can be visually estimated. The main difficulty with this procedure, however, is that conclusions drawn contain some element of subjectivity and as such the VP-8 technique should not be considered as a replacement for an objective, large number sampling algorithm discussed above. On the other hand, the VP-8 procedure is currently the only method available to us for incorporating large data samplings in our analyses and the consequent increase in accuracy by such data samplings has been discussed. In addition, departures from good correlation are readily apparent in the VP-8 reliefs as distortions because of the graphic and natural way intensity data is presented. Thus, in the absence of an objective, large number sampling algorithm which calculates ρ^2, the VP-8 imagery should be a reasonably good indicator of distance correlation and considerably better than our previous, small sampling technique discussed above. Let us now examine the Shroud image for possible distance information encodement with the VP-8 system. Figure (6) shows the VP-8 relief surface of the frontal full body image, (Ref. 17). Figure (7) shows the relief surface for the facial image, with high frequency noise removed by slight defocusing during scanning. In both Figures (6) and (7), the VP-8 relief surfaces seem to correspond closely to a physiologically reasonable body shape, thereby demonstrating a definite correlation of image intensity with distance.

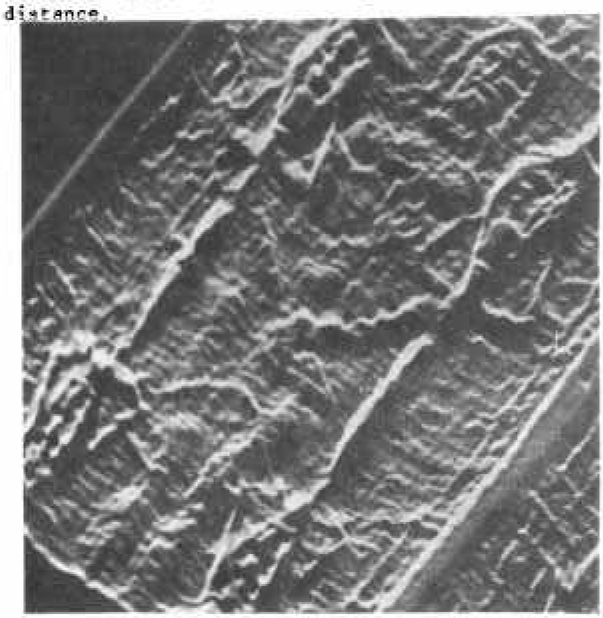

Figure 6. VP-8 of Shroud Frontal Image

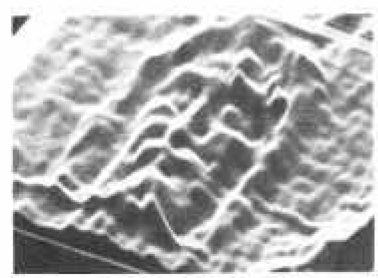

Figure 7. VP-8 of Shroud Face

D. Comparison of Relief Image to Body Shape. It is difficult to evaluate how close the VP-8 Shroud relief of Figure (6) is to a body shape as it appears on a CRT. However, if it were reproduced as a full-size physical surface, correlations with a human form would be possible. To accomplish this, we traced 570 cross-sectional lateral profiles of the Shroud image onto 1/8 inch corrogated cardboard which were cut and stacked as shown in Figure (8). On this model, the shoulders are missing because that image area was burned away during a fire in 1532 (Ref. 1). Diamond shaped water marks, also due to this fire event and certain creases appear as relief structures on the image surface because they possess shading of their own; these anamolies should be regarded as noise. We then compared selected profiles of the stacked cardboard with those of a volunteer subject who assumed the position indicated by the Shroud image (which we ensured was correct by covering him with a cloth model containing an image of the Shroud and positioning him accordingly in the x-y plane.) This comparison indicated that the VP-8 image modelled relief variations, z, of a human form over small-scale horizontal distances (Δx, Δy = 10 cm) but generally failed to model relationships of vertical relief between image locations separated by large-scale distances. For example, the set of image points in the vicinity of the nose (i.e., eyes and lips) had a reasonable relief structure between themselves as did the fingers of the hand. However, the large-scale relief relationship between the hand and nose areas were not correct. This lack of large-scale relief correlation gives the VP-8 image a flat or stiff quality (See Figure 8-A). This effect might imply that the correlation of shading with distance varies from region to region over the image, but then it would be difficult to understand how, with one correlation function applied globally over the body image, the VP-8 relief is apparently correct within small-scale neighborhoods of any and all image points.

In an attempt to understand why the VP-8 image failed to correlate relief over large-scale distances, we sought to define how and where the VP-8 image is distorted from an anatomically correct human form. Our procedure was to numerically distort the flat reference surface upon which the VP-8 relief was generated in such a way as to bring the VP-8 relief into correspondence with the body surface of a volunteer subject. Departure of the reference surface from flatness would be then a measure of how the VP-8 Shroud image departs from a body shape. To determine the characteristics of such a deformed reference surface, each of the 570 tracings were digitized onto an HP-9830A computer (Ref. 18). At 18 locations along the longitudinal midline of the Shroud image, where major curvature changes of the body occur, we calculated horizontal contours of the reference surface required to bring the VP-8 Shroud profiles into correspondence with the associated profiles of the volunteer subject. From these reference contours we generated profiles for the remaining 552 contours by linear interpolation. In this way, we defined a mathematical surface which deformed the VP-8 image into an anatomically correct body surface, the latter of which is shown in Figure (8-B).

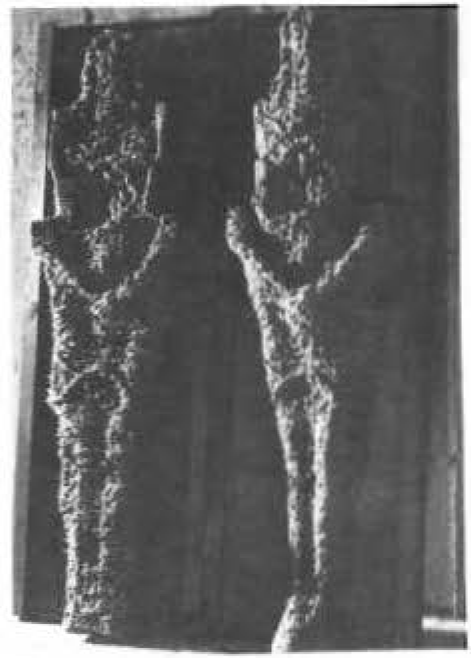

Figure 8. A. Cardboard Model of Shroud VP-8.
B. Cardboard Model of Derived Shroud VP-8.

Figure (9) shows the reference surface used to calculate the "derived" VP-8 image which mathematically is the difference of the VP-8 relief of Figure (8-A) and the derived VP-8 image surface, Figure (8-B). We note that the distortions in the reference surface occur at generally lower spatial frequencies than image features such as the nose, lips, eyes, fingers, etc. Therefore, the reference surface modifies only the low frequency Fourier components of the VP-8 image and does not introduce extraneous information into higher frequency components of the Shroud image where, for example, facial characteristics are defined. Accordingly, the "derived" VP-8 image is like the volunteer subject at low frequencies but like the VP-8 image at high frequencies.

Strictly speaking, the reference surface of Figure (9) is a geometric representation of how the VP-8 image of Figure (8-A) differs in relief from a body shape. However, an interesting observation of that surface is that it resembles the geometrical characteristics of a cloth as it might naturally drape over a body shape. Figure (10) shows a linen cloth draping over the "derived" VP-8 image and the close resemblance of this surface with the reference surface of Figure (9) is noteworthy, especially since the general layout of the body image on the shroud seems to suggest that the body was wrapped in the Shroud at the time of image formation.

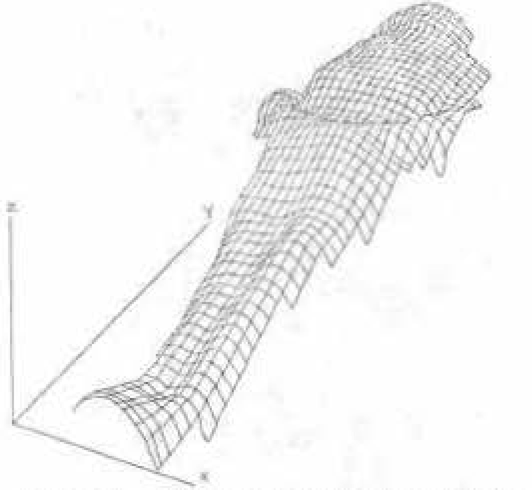

Figure 9. Deformed VP-8 Reference Surface

Figure 10. Linen Cloth Draping Over Derived Image

It should be noted that such a result does not automatically occur for images of a human form where shading is correlated with distance. As an example, consider the VP-8 relief of the distance encoded image of Figure (3-B). Since this image was produced relative to a flat reference surface, the VP-8 relief image is correct as it stands and therefore the reference surface requires no modification. For such an image it would be impossible to interpret the flat reference surface as a "draping" cloth over the face. Cloth-drape distortions can be induced into the phosphorescent head image if the reference surface of the attenuating liquid is appropriately deformed. We produced such an image by placing the phosphorescent head face down in a clear plastic container whose bottom was deformed into the shape of a cloth draping over a face as determined by experiment. This container was filled with a light absorbing liquid, in the same manner that Figure (3-B) was produced, and the head photographed. The resulting VP-8 relief is shown in Figure (11). Comparison of this

Figure 11. Phosphorescent Face Relative to Curved Surface.

relief with the one of Figure (5-B) shows obvious convex upward distortion. If we were to deform the VP-8 reference surface of this image into an appropriate concave shape so as to make the deformed face appear as the VP-8 facial surface of Figure (5-B), the reference surface would assume the shape of the plastic container.

These results demonstrate that image shading on the Shroud correlates with distance between two surfaces, one of which can be interpreted as a body shape and the other as a cloth draping over that body surface. Logically, this does not prove that a cloth was draped over a body shape when the Shroud image was formed because other hypotheses not involving a cloth covered body shape might conceiveably account for such an effect. We consider, in the hypotheses section of this paper, several hypotheses which fall into such a category. The interpretation that the Shroud covered a body shape is nevertheless self-consistent in that the "cloth" surface, calculated so as to bring the VP-8 relief into an anatomically correct body shape, has the correct geometry for a cloth draping over the body shape, which need not necessarily be so. It is also noteworthy that this self-consistency has been achieved via a single mapping function, I(d), which applies globally over the entire frontal image, thereby providing a certain elegance and simplicity to the interpretation. We further note that the ability to independently interpret certain lateral two dimensional distortions in the body image as due to cloth drape (Ref. 19) gives the above interpretation an additional realism.

Thus, we may refer to the Shroud image as having a "three dimensional characteristic" which means, simply, that image shading can be self-consistently interpreted as being correlated with the distance between a body and an enveloping cloth. If the Shroud did, in fact cover a body shape at the time of image formation, then the interpretation is physically valid; if, however, the shading structure was the result of some other mechanism which did not require that the cloth covered a body, for example by an artist or bas-relief, then we should regard the "three dimensional interpretation" as a convenient device for describing the shading distribution on the Shroud. Whichever may be the case, a correct hypothesis of image formation must be able to produce an image structure capable of a "three dimensional interpretation", for in doing so the shading distribution of the shroud image would be duplicated. It is in this sense that we consider a variety of image formation mechanisms in the hypothesis section of this paper.

We should point out that it is improper to discuss the validity of the "three dimensional interpretation" without first considering specific image formation mechanisms which might produce the Shroud image's shading structure. For example, if we were to tacitly assume that the three dimensional interpretation is physically valid, then we would automatically exclude image formation mechanisms which might be capable of reproducing the Shroud image's shading but not require the cloth to cover a body shape. Thus, the three-dimensional interpretation of the Shroud image should not necessarily be regarded as a demonstration that the Shroud covered a body shape at the time of image formation, although this is consistent with the data, but as an image quality (or observation) which a given image formation hypothesis must be able to produce. This is not to say, however, that the three dimensional interpretation's value is simply as an observational characteristic to be explained by a given hypothesis; it also suggests that, in some sense, surface geometry of a body shape is an implicit factor in image generation, an insight potentially useful in formulating image formation hypotheses.

We should also note that, as a point of logic, if a hypothetical mechanism were shown to produce an image capable of a three-dimensional interpretation, this does not necessarily imply that it is therefore <u>the</u> mechanism which formed the Shroud image; there <u>may</u> be other mechanisms which could also do the same thing. The scientific ideal is to test all such mechanisms against other independent data (chemistry, microscopy, historical, etc.); and if these observations are sufficiently discriminating, the correct hypothesis should stand alone. There is, however, no guarantee that sufficient scientific information is associated with the Shroud image to achieve such a desired result. A general approach of hypotheses testing has been taken by Schwalbe and Rogers (Ref. 3), while in this paper we examine image formation hypotheses against mainly the three-dimensional characteristic of the Shroud image.

III. IMAGE FORMATION HYPOTHESES

A. Discussion. In this section, we discuss various image formation mechanisms which have been proposed in terms of how well these mechanisms produce shading structures capable of a three-dimensional interpretation, with the Shroud image as the basis of comparison. We also discuss these mechanisms with respect to other image characteristics where appropriate. Because the Shroud image admits a three-dimensional interpretation, we only consider hypotheses which start with a body shape and transform the shape, by some process, into shading. Though this may or may not involve directly a cloth covered body, it is difficult to conceive of an image-producing mechanism which does not, in some way, incorporate body shape data so as to produce an image structure that we see on the Shroud. We might, for example, hypothesize that the Shroud discolorations were produced by some random staining process with no body shape involved whatsoever. But this would be extremely "ad hoc", given the general complexity and subtlety of the image. Thus, we are in essence studying how well various image formation mechanisms transport (distance) information from a body shape to the Shroud. It is therefore possible to consider these mechanisms in terms of Shannon's communication model of information transfer (Ref. 20) if we regard a body shape as a "geometric message" to be communicated to the Surface of the Shroud as shading by the hypothetical process. This process may be, for example, molecular diffusion from a body to the cloth or some eye/brain/hand coordination technique of an artist who in essence converts previously experienced body surface data into shading. Shannon's general assumption is that all communication consists of three stages: encodement, channel transfer, and decodement; hence, any image formation mechanism which converts body shape information into shading would have to, in some fashion, perform these three functions. Accordingly we are not concerned just with whatever interaction took place at the surface of the Shroud to produce shading, for this is in essence Shannon's third phase, but with complete information transport from a body shape to the Shroud, which may or may not involve directly a cloth-covered body (at the decodement stage).

Our approach was to experimentally model general categories of image formation processes which might have been responsible for producing the Shroud image. Each experimental image was evaluated by the VP-8 process for its relative ability to encode distance information into shading, with the Shroud image as the basis for comparison. For standardization purposes, all experimental images were produced from the same facial shape as shown in Figure (3-A). We also estimated ρ^2 for each image by the Small Sample Correlation Technique involving the same 13 data points we sampled on the Shroud as discussed above in Section II. For all cases, the correlations were sufficiently low that the 95% confidence intervals overlapped thereby rendering discrimination based on relative values of ρ^2 essentially meaningless. However, if roughly 2000 data points could be correlated for each image, discriminations should be possible. Until this can be achieved, the VP-8 analyses presented below for each experimental image should be regarded as preliminary although in some cases reliefs are sufficiently distorted that definite conclusions are possible.

Each VP-8 relief is presented at an angle such that the relief variations can be seen relative to the planar distribution of image features. When studying each relief image, care should be taken not to confuse the quality of the relief with how well image features are distributed two-dimensionally over the reference surface. In some cases this distribution can be quite accurate because the process considered may be capable of rendering accurate planar placement of image features. The quality under consideration is rather how well the relief, not the planar layout, models a human face.

B. Artist. The first hypothesis category we consider is that the Shroud image was the work of an artist. By artist we mean one who places an image on cloth by some eye/brain/hand coordination technique, like painting. This is probably the oldest documented hypothesis of image formation. As far back as the fourteenth century, a bishop made this claim but unfortunately did not provide us with either the name of the artist or the technique used (Ref. 1). At the turn of the century Thurston (Ref. 21), and more recently McCrone (Refs. 22-24) supported this hypothesis, the latter studying microscopic samples from the Shroud. However, Heller and Adler (Ref. 4) who examined Shroud samples with a comprehensive series of microchemical analyses disagreed with these conclusions, as have various scholars and scientists (Refs. 3, 25).

With regard to the hypothesis that an artist created the Shroud image, there are two fundamental questions which should be asked. 1. could an artist shade an image on cloth so as to encode distance information of a body shape relative to a draping cloth with the precision that exists on the Shroud? 2. Would an artist either conceive of or be compelled to attempt such a correlation?

To address the first question, we conducted a series of experiments with professional artists in an attempt to evaluate how well they could shade an image with distance. We based our experiments on Shannon's communication model of information transfer taking care that at each phase of information transfer the artist would not be at a disadvantage or advantage from what a medieval artist might be able to achieve in an eye/brain/hand coordination sense, but with three noteable exceptions. We did not require the artists to incorporate cloth-drape effects into their work, nor did we ask them to create images on flexible, absorbant linen cloth. We also did not require the artists to compose images of the full body, rather only of the face.

For our experiment, we secured the assistance of two certified criminal artists (Ref. 26, 27) for such artists, in the course of their professional work, compose realistic, monatone imagery, qualities found in the Shroud image. In one set of experiments, we asked the artists to "freehand" shade an image of a given reference face, the same used in Figure (3-A), in proportion to relief. In a second set, we provided the artists with relief data at 15 specific "anchor" points on the face (i.e., lips, nose, cheeks, etc.). The artists then constructed an encoder by which they could convert distance information into shading. This encoder was a continuum of shades which corresponded to various relief distances. Once these anchor points were established to the ability of the artists, the artists roughed in the rest of the image by interpolation, using the reference face as a guide. Since this second set of experiments incorporated measured relief values of the face, we refer to it as the "rigorous" experiment. In both the freehand and rigorous experiments, we constrained the density range of the images to be no more than 0.10, essentially for that presently observed on the Shroud (0.09). The density of the drawing paper, however, was selected to be approximately that of new linen, 0.24. The procedure used by the artists was the same pencil shading technique as used in their professional work. We assumed that this method of application provided the greatest control of shading to the artist; otherwise criminal artists would probably be using some other technique to meet demand for realism in their profession. Although not clear how this could be accomplished in the case of the Shroud image, subtraction of overshading was accomplished by simple erasure and all images drawn were full-size. In no case were the artists provided with densitometric data of their images, such as via the VP-8, for we can conceive of no way that a medieval artist would be able to evaluate the quality of his or her work with some equivalent technique.

In essence, then, these artists performed Shannon's three stages of information transfer: encodement is collection of body shape data (either visually or by measurement), channel tranfer is by the internal workings of the artist's eye/brain/hand system, and decodement is the process of placing the shape information into a shading distribution. Thus, in a real sense, these artists can be viewed as an information transfer process.

In addition to the images produced by the artists as described above, we also asked them to prepare images where some of the above constraints were removed so as to determine their relative importance. We provided the artists with high contrast black and white photographs of the reference face taken through an attenuating medium, such photographs being encoded with distance information as discussed above. Thus, we photographically performed the encodement process rather than allow the artists to do it. The photographs also served as a decoder and accordingly all the artists had to do was to copy the "decoder photograph". We also relaxed the constraint of 0.10 shading variation for the artists to the entire density range. Although this experiment gave overwhelming advantage to the artists over a hypothetical Shroud artist, we thought it would be of interest to define the precision of the decodement process by this procedure.

Figures (12) to (17) show VP-8 reliefs of all experimental images. Generally, all images exhibit some correlation with facial relief; this shows that an artist is capable of producing images with shading that contains some degree of distance information. We also note, that all VP-8 images are quite different from each other, although they were all generated from the same facial shape. This implies that an artist, when viewed as an information transfer process (for distance) is to some extent stochastic in nature. This is in contrast to other mechanisms discussed below which are capable of repeatability. Figures (12) to (15) show the rigorous and freehand attempts of Artists A and B. These images, when compared to the Shroud VP-8 reliefs do not seem particularly convincing and in general have a mask-like quality about them. Each image possesses relief deformities, particularly in the lip regions. The VP-8 reliefs of the rigorous compositions do not show a significant improvement over the freehand versions which probably indicates that the "artist mechanism" has a limit as to the precision by which distance information can be transferred. In Figures (16) and (17) the VP-8 reliefs, are noticeably improved and in our opinion approach the quality of the Shroud image. These images, however, are the result of the artist's copying a distance encoded photograph with the contrast restrictions removed.

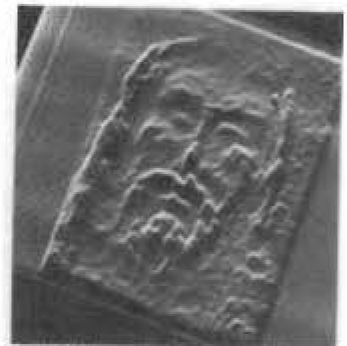

Figure 12. Artist A - Rigorous.

Figure 13. Artist B - Rigorous.

Figure 14. Artist A - Freehand.

Figure 15. Artist B - Freehand.

Figure 16. Artist A - Copy of Photo.

Figure 17. Artist B - copy of Photo.

The physiological reason for the variance in artist copies and a general lack of good correlation is unclear, but image contrast is a probable factor. In Turin, the authors (Jumper & Jackson) as well as other scientists (Ref. 3), were unable to visually discern image patterns on the Shroud (under illumination of photographic lights) at distances closer than about six feet. Janney (Ref. 3) explains this phenomenon as due to inhibition effects in the human eye when observing faint images. We further suggest that critical band masking (Ref. 28) of the image by the weave of the cloth could also be a factor. If an artist were to create an image of such a low contrast on cloth with the requirement that shading be correlated with anatomical relief of a human form, it is unclear how this could reasonably be achieved. The artist could possibly observe the progress of his work from afar, but wouldn't be able to reliably shade the image by hand because the Shroud image cannot be discerned up close. It is conceivable that the relative contrast of the image was at one time better than what it is at present, thereby allowing an artist greater visual latitude by which to encode distance information. This possibility should be given further study and is generally beyond the scope of this paper. It would seem, however, that the global nature of the three dimensional correlation of the Shroud image and precision implied by the VP-8 studies would be difficult to reconcile with possible spatial nonuniformities resulting from a shading structure that varies significantly with time.

We showed above that the Shroud image contains cloth/drape-like effects in the low frequency components of the image while small scale body surface characteristics (i.e., lips, fingers, etc.), reside in the high frequency part. It is unclear how an artist could achieve such an effect because he would have to, in essence, observe body and cloth surfaces simultaneously in order to transform their relief characteristics into a single shading distribution. However, lateral distributions in the image due to cloth-drape (Ref. 19), would be easier to encode because the cloth could be first draped over a body shape so as to allow blood staining to register body image locations. However, the artist would have to be fully aware that such distortions must occur because the image is also laterally distorted where blood marks are not present, for example at the fingers (Ref. 19).

2. Consider now the second question: Would an artist encode distance information into the image? In addressing this question, we must avoid projecting modern conceptions of how an artist should create a "Shroud image" upon a hypothetical artist in the middle ages (or before). For example, McCrone (Ref. 24), argues that shading an image with distance is the natural way for an artist to place a body image on cloth, since locations where the body comes closer to the cloth would be locations where the shading should be more intense. We don't question whether a medieval artist is capable of thinking in such terms, but we do question whether this might be an unwarranted extrapolation from twentieth century mode of thought to a medieval way of thinking. In essence, such a conception involves thinking of how the cloth would respond to some abstract emanation from the body and how such a response pattern on the cloth should appear. It is beyond the scope of this paper to address the validity of this type of thinking from a historical perspective but we do point out that, to our knowledge, there is no example in medieval art history where the image of Jesus as painted on cloth (like in Veronica's Veil or Eastern Iconography) is encoded with distance information. Rather, such images appear as though the cloth was acting as a mirror to see the image of Christ (Ref. 1). We suggest, therefore, that a medieval artist would have thought in terms of how the cloth might appear as if it were reflecting the image of a body rather than absorbing it in inverse proportion with distance. Thus, an artist would probably create an

albedo rather than a distance encoded image, since that seems to be the type of image consistent with historical examples of Christ's face on cloth. It is noteworthy that such examples, associated with the legend of Veronica placing a towel on the face of Christ and receiving an imprint, afforded many artists with opportunities to create a distance encoded image, but there seems to be no instance where this was done, presumably because such an image structure simply did not occur to the artist. In this regard, we must not argue that the Turin Shroud is one example of this attempt by an artist, for this begs the question since the Shroud cannot be both object of study and an independent data source at the same time.

For these reasons, we are skeptical of the artist hypothesis as an adequate explanation for the Shroud image's shading structure, but we are open to and recommend additional studies.

C. Direct Contact. The next category we examined consisted of those images which can be formed by direct contact with a human body or statue. Direct contact models are usually proposed to explain the two dimensional layout of the Shroud image as revealed through photographic reversal or the image's high resolution. Generally, the images produced in this manner can be expected to have a binary shading distribution; shading of some constant value is recorded where cloth contact occurs leaving the cloth at the background value where it does not. Such binary characteristics pose a fundamental problem with this type of process in encoding distance information, for such binary behavior does not provide necessary latitude to encode relief variations. We investigated this mechanism by uniformily covering the same reference face discussed above with printer's ink and placing a cloth over it to receive the image. Immediately obvious was the lack of contact of the cloth over many locations (for example, side of nose). Since the Shroud image shows color in these locations, we gently conformed the cloth to make contact.

Figure (18) shows the resulting VP-8 relief. The VP-8 relief is highly distorted, having a plateau-like structure due to the essentially binary nature of the direct contact process. These distortions are sufficiently large that we reject the simple direct contact mechanism, described above, as a reasonable explanation for the Shroud image. Perhaps more complex direct contact mechanisms, for example suggested by German (Ref. 3), may show some improvements (although to date attempts have not been convincing).

D. Action-At-A-Distance-Mechanisms

1. Diffusion. Probably the earliest

Figure 18. Direct Contact

proposed action-at-a-distance mechanism was Vignon's "Vaporograph" where ammonia molecules from a perspiration covered body diffuse to the enveloping Shroud where they are absorbed and stain the cloth, thereby producing an image (Ref. 7). In terms of Shannon's formalism, evaporation from the body surface is the encodement process, diffusion or random walk of the molecules is the channel transfer, and absorption characterizes the decodement process. Informational noise with respect to the shape information which is tranferred by this process occurs in the channel phase as diffusive spreading.

To experimentally model the diffusion process via molecular transport, we quickly demonstrated that molecular diffusion is significantly perturbed by small convection currents and masked by shading enhancement effects at cloth contact points through capillary action. To decouple these unwanted effects from our investigation of the diffusion mechanism by itself, we constructed a paraffin model of the space between the reference facial shape and a draping cloth over that face as characterized from cloth drape data (Ref. 29). Since temperature obeys the diffusion equation, we attempted to model molecular diffusion by temperature diffusion through the paraffin mold whereby convection and contact point enhancement effects were effectively eliminated. In order to ensure good thermal contact with all points on the cloth surface of the paraffin, we floated the paraffin in room temperature, 77°F water. In the facial depression of the paraffin we placed approximately 100°F water which we kept agitated so as to ensure that the facial surface was always nearly at uniform temperature. We examined the temperature image on the cloth-surface side of the paraffin with an AGA-780 thermovision system which detects emitted infrared radiation in the 8-14 micron region. The diffusion coefficient for paraffin is 9.7×10^{-4} cm^2/S whereas for water it is 14×10^{-4} cm^2/S (Ref. 30). The closeness of these coefficients coupled with the uniform thermal con_act provided by water immersion meant that the paraffin/water interface was essentially transparent to temperature diffusion. Thus, the temperature distributon on the cloth surface as revealed by the thermovision should be a realistic depiction of a general diffusion image. We note that the temperature variations of our diffusion image were no greater than several degrees Farenheit, much smaller than 100°F - 77°F = 23°F temperature difference from face to cloth. Thus, this experiment approximated the boundary condition of complete absorption on the cloth for which molecular concentration or, in this case, temperature variation at the boundary would be zero.

Figure (19) shows the experimental image and VP-8 relief. Large scale facial structures are apparent in the photographic image although resolution of fine structures such as the lips are absent. It is significant that the Shroud image is not blurred to this degree. The VP-8 relief appears to be somewhat deformed, particularly in the cheek area which seem to protrude upward, giving the VP-8 relief a convex quality. This effect is associated with the fact that the reference surface where the image was observed by the IR camera was curved, similar to a draping cloth. In Figure (11) we presented a VP-8 relief which shows the effect of cloth-drape. This relief may be compared directly with the diffusion VP-8 relief because the paraffin form and plastic container used to generate the Figure (11) relief were made from the same mold. (See discussion of Figure (11)).

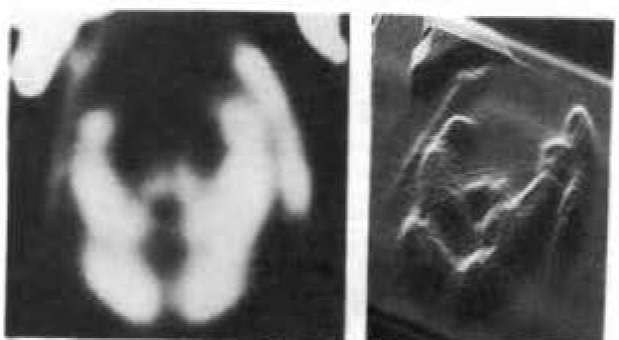

Figure 19. Diffusion

Thus, the diffusion process seems capable of encoding body shape and cloth-drape information into image structure, but only in the low frequency part of the Fourier spectrum. High frequency components, necessary to define facial details are not generated owing to diffusive spreading. Since this is not the case for the Shroud image, we must reject the diffusion hypothesis.

2. Radiation. In diffusion, information is tranferred by the random walk of molecules. In radiation, the carriers of information propagate along straight line paths as photons. If radiation is Lambertian such as blackbody infrared radiation (Ref. 31), then no shading variations will occur in the resulting image; it will appear as a uniform discoloration. The essential reason is that each radiating surface element of the body surface emits isotropic $1/r^2$ radiation while each receiving element on the body surface sees a surface area on the body that increases as r^2. These two effects cancel leaving each surface element receiving the same radiant flux. Such a condition obviously transfers no distance information since one shading level is recorded regardless of the cloth-body distance. We modeled this situation by coating the reference face with phosphorescent paint which when optically charged becomes a Lambertian emitter. We then contoured sheets of sensitive photographic film over the face to model a draping cloth (Ref. 32). The developed image was of uniform intensity thereby showing a Lambertian character.

However, not all radiation situations need be Lambertian. If aniotropies or attenuation of the radiation occurs as it propagates from body to cloth, shading variations in the resulting image will be present. To model this configuration, we performed the same photographic experiment described above for Lambertian radiation but in a light attenuating liquid medium. Images so formed would be expected to contain shading variations which could be correlated with film-body distance, although resolution would probably be somewhat degraded in these images.

Figure (20) shows the VP-8 image for a radiation image formed by this technique. Generally, the VP-8 relief resembles the VP-8 diffusion relief of Figure (19-B). Since cloth drape information is present in this image, the remarks made for diffusion apply. As with the diffusion image, there is a lack of resolution of facial details, although the lips are just resolved. We have produced, in Figure (3-B), a distance encoded image by radiation which has excellent correlation and can include cloth drape effects. But we have not thought of a reasonable way to incorporate its collimation effect (via a camera looking through the light attenuating medium) into some equivalent hypotheses for the Shroud image. For these reasons and by comparison with the VP-8 Shroud relief, we conclude that the radiation from a full body shape is probably unable to account for the Shroud image.

3. Bas-Relief. As previously noted, the general lack of resolution for diffusion and radiation mechanisms acting from a body surface is a major problem for these processes. However, one

Figure 20. Radiation.

possibility for solving the resolution problem is to use a bas (partial) relief of a body shape as suggested by Ashe (Ref. 33). One might envision such a relief being covered with a cloth and some action-at-a-distance mechanism, such as thermal diffusion, operating to produce shading inversely proportional with cloth to bas-relief distance.

As an initial evaluation of the bas-relief hypothesis, we heated a five centimeter diameter medallion containing a roughly millimeter thick bas-relief image of the Shroud face and covered it with Watmann #1 filter paper. The scorched image and VP-8 relief are shown in Figure (21), and the reasonably close resemblance with the VP-8 relief of the Shroud was noted. We therefore decided to examine this mechanism in more detail using a full-size bas-relief of the reference face. This experiment is best described in terms of Shannon's formalism.

The use of a bas relief makes sense only if it contains distance information of a human shape. That is, if $z = u(x,y)$ is the surface equation characterizing the given human shape, where z is the relief coordinate, then the surface equation of the bas-relief must be of the form $z' = g(z)$, where for all coordinates (x,y), $z' \ll z$. The encodement process would obviously be performed by a human agent and is defined as the construction of the surface, $z'(x,y)$, from some $z(x,y)$. What is especially attractive about the bas-relief hypothesis is that a sculpturer could probably achieve reasonably correct distance encodement into his bas-relief without realizing he or she was doing so. This could be achieved by illuminating the bas relief with grazing angle light. If the bas-relief were correctly encoded with distance information, the shadow lengths over the bas-relief would have the same relative distribution as the full three dimensional relief being copied, but when more normally illuminated. In our experiment, we performed the encodement process with the VP-8, assuming that a skilled sculpturer could achieve the same result, as evidenced by the experiment with the medallion above. We constructed a topographical map out of stacked paper contours each representing a specific shading level of the distance encoded image of the reference face in Figure (3-B). From a mold of the topographical map, we then prepared a bronze cast. This bronze model then contained distance information of the reference face and had the dimensions, 23 cm long, 1 cm thick (at the highest). We compared various profiles across the finished bas-relief with low-gain VP-8 profiles for the distance encoded image. These profiles compared very well and we were therefore assured that distance information had been properly encoded into the bas-relief. The construction of the bas-relief can be regarded as Shannon's encodement phase of the information transfer from a full body shape to the cloth.

For the decodement process (the channel transfer is trivial in this case), the bronze cast was heated and impressed into a stretched cloth. The heat transfer to the cloth at any location occurred by thermal diffusion and as previously discussed, the distance information resident in the bas-relief should be transferred (or decoded) into the cloth as thermal discolorations of varying shades and with high resolution. It is noteworthy, inasmuch as the Shroud image seems to contain cloth-body rather than simply body-distance information, that the bas-relief mechanism should also transfer cloth-body type information even though it involves a nearly flat relief. The reason is that when the cloth is stretched over the bas-relief, the cloth assumes a slightly warped shape, but one which is scaled down in the z-direction from a cloth over a full body shape by essentially the same scaling factor, $g(z)$, as for the body. Then, when the resulting image is viewed by the VP-8, the scaling can be compensated for by a relief gain adjustment. Thus, a hypothetical craftsman need only work at encoding body distance information and the cloth-drape information is placed naturally into the image during decodement, unlike in the artist hypothesis where body and cloth drape information must be consciously placed into the image by the human agent. It would seem, therefore, that a bas-relief mechanism is theoretically capable of producing an image structure capable of a three-dimensinal interpretation of a full body under a draping cloth, even though a partial relief is used. This does not mean, however, that information of a body shape is not used, because the bas-relief itself is derived from a full-body shape.

Figure (22-A) shows the resulting discoloration image pattern's VP-8 relief. We note first that the relief image has a convex quality similar to that of Figure (11) which was generated relative to a curved surface approximating a

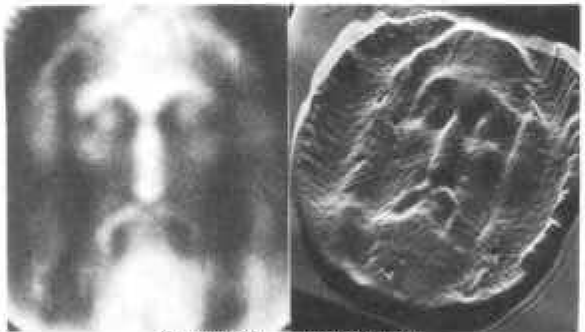

Figure 21. Medallion.

draping cloth. Thus, the notion that cloth-drape effects can be placed into an image by the bas-relief mechanism seems valid. The image has good resolution and exhibits a relief structure similar to, but not quite as good in detail as the Shroud VP-8, and has a slight plateau appearance, like in the direct contact VP-8 image. We do note, however, that the medallion VP-8 does seem to compare rather well. Thus, we conclude that the bas-relief mechanism might be capable of producing an image that correlates with cloth-body distance to the degree present in the Shroud image as well as providing an acceptable degree of resolution. Furthermore, the mechanism is historically credible since bas-reliefs have been produced by sculpturers for centuries. In addition, this mechanism generates an image with a chemical structure similar to that observed on the Shroud (Ref. 4).

This, however, does not mean that the bas-relief mechanism is compatible with all Shroud image characteristics. There are some major problems which should be pointed out. First, it is difficult to see how thermal discolorations can be placed by the bas-relief mechanism only on the upper fibrils of the cloth, as on the Shroud (Ref. 3). Regardless of the temperature of the bas-relief, we observed that thermal discolorations on the reverse side of the cloth occurred within several seconds of cloth placement on the hot bas-relief. For our experiments we used 350 micron thick linen, similar to the Shroud (Ref. 3). Thermal effects propagate a distance, d, in a characteristic time, $t = d^2/D$ where D is the thermal diffusivity. Let us conservatively assume that Shroud threads are 10 fibrils thick. To discolor the the first fibril layer, the time required would be

$$t' = \left(\frac{d'}{d}\right)^2 t \qquad (4)$$

where t is the time (several seconds) to scorch the entire thickness d of cloth, and d' the thickness of the first fibril layer. Then with $d'/d = 10\%$, we may calculate t' to be on the order of several hundredths of a second, a time which would pose considerable technical difficulties for a hypothetical craftsman trying to make a Shroud image. Furthermore, even if he could achieve this or perhaps by extending the scorching time somewhat by dampening the cloth, it is unclear why he would feel compelled to place an image on only one side. For then, he sacrifices the ability to visually follow the progress of image development by observing discolorations as they appear on the reverse side. We produced images on wetted linen cloth and found that the time to produce an image was increased up to roughly 30 seconds owing to the fact that water had to first be vaporized away before fibril scorching could take place.We succeeded in placing an image on one side of the cloth by this technique but contrast problems, causing the VP-8 Relief to appear more like a direct contact image (See below), were more severe because unscorched fibrils were protected by water. We also noted that evaporation was somewhat nonuniform leading to noticeable nonuniformities in image discoloration. A VP-8 relief of an image formed on wet linen is shown in Figure 22-B.

Another difficulty lies in image contrast. The maximum shading of the Figure (21) medallion and Figure (22-A) full-size bas relief images was much greater than the Shroud, approaching a deep brown scorch. This high intensity of shading at contact points was necessary in order for the more distant parts of the bas-relief to record their patterns on the cloth and is the probable reason for the slight plateau effect in the VP-8 relief noted above. It thus appears as though linen has a thermal response such that exceedingly low bas-reliefs are necessary to produce an image with an overall contrast variation as subtle as on the S..oud. The construction of such a relief may pose significant technical problems for a hypothetical craftsman; we note that our bas-relief was 1.0 cm thick at the maximum (nose to background) and the medallion relief was considerably lower, on the order of a millimeter. We also constructed a thicker bas-relief (2.2 cm thick) and observed that the contrast problem was more pronounced.

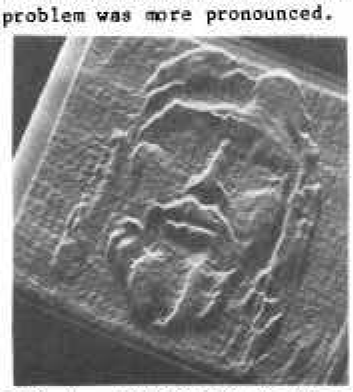

Figure 22-A. Bas Relief on Dry Linen

Figure 22. B - Bas-Relief on Wet Linen.

A final problem is that lateral distortions in the Shroud image consistent with a cloth draping over a full body shape, have been observed (Ref. 19). Such effects are not produced by the bas-relief mechanism since the cloth is essentially flat at the time of image generation. It is conceivable that a craftsman could two dimensionally deform his bas-relief to simulate lateral cloth-drape distortions, but this complicates an otherwise simple mechanism and it is not clear if such a concept would occur to a medieval craftsman. Such a possibility could be studied via historical images of Christ's face on cloth to see if medieval artists produced distorted images to account for cloth drape , but of the several such images we have examined, for example in Reference 1, there is no indication of such distortion. Except for the latter problem, some of these difficulties may be overcome by using chemical instead of thermal diffusion. We have not investigated this except to note that chemical transfer is susceptible to bright spots appearing at contact points due to capillary action and the chemistry of the Shroud must be reproduced. With these considerations, we are generally skeptical of the bas-relief hypothesis although this mechanism might be capable of producing images with a three dimensional characteristic and suitable chemistry; this, however, still needs to be demonstrated with a full-size bas-relief of a face and body.

4. Nickell Powder Technique. Although not strictly an action-at-a-distance hypothesis, another bas-relief based mechanism has been proposed by Nickell (Ref. 34) and involves contouring cloth to the bas-relief and "dusting" the deformed cloth surface so as to produce an image. Since the bronze bas-reliefs discussed above were encoded with distance information of the reference face, we used one (with dimensions 23 cm long, 2.2 cm thick (maximum)) as the basis of the experiment. We conformed, as Nickell indicates, wet linen to the bas-relief so as to make all image features (eyes, lips, etc.) impressed into the cloth. We then "dabbed" the cloth with fine tempra powder. The best result was an image shown in Figure (23) where shading essentially correlated with local curvature of the face (since that is where powder tended to accumulate). Thus, the shaded image seemed to contain more curvature rather than distance information of the face. In addition, we noted large quantities of powder falling through the cloth weave structure and accumulating on the reverse side. Accordingly we conclude that this mechanism is unacceptable.

5. Engraving. Thus far, we have considered action-at-a-distance mechanisms in which the encodement process (i.e., evaporation or emission) is from a surface which contains three dimensional information by virtue of that surface having a three dimensional shape. Alternatively, Schwalbe and Rogers (Ref. 3), have proposed a mechanism where this need not be so. In their model, the surface is a flat metal sheet and the encodement of body shape information is via engraved lines which in essence changes the effective thermal emissivity from point to point over the surface. They suggest that the Shroud might have been suspended above a heated engraving and discolored by radiant heat. A necessary condition for this mechanism to work is that the emissivity be encoded with appropriate distance information; that is, the number density of engraved lines should correspond to cloth-body distance.

As an experimental examination of the engraving hypothesis, we produced images from special engraving simulations we had prepared. In this regard, consider again Shannon's information transfer model, in particular the encodement phase. Rather than test how well an engraver could encode distance information (a process already examined under the artist hypothesis - if we assume the equivalence of engraving to drawing), we produced the equivalent of an engraved

Figure 23. Powder Technique

surface which we coded with distance information photochemically. The procedure was to photoetch the distance encoded image of Figure (3-B) onto a copper plate, thereby simulating the rough surface of an engraving. The final result was an effective emissivity which depended on a dot pattern such that the dot size varied with image shading or, equivalently, distance. We chose copper because it has a sufficiently high melting point when heated to scorch cloth and is considered an ideal metal for engraving. Our experiments involved examining the radiant emissions from the copper etchings with the AGA thermovision and producing thermal images on Whatman #1 filter paper by direct contact.

Figure (24) shows the infrared emission image and associated VP-8 relief. Although the degree of etching was correlated with the relief structure of the plaster reference face, the emission intensity does not seem to preserve this correlation and accordingly neither would the shading structure of any image scorched onto cloth by such a radiant distribution. The reason for the lack of correlation is, however, interesting. Consider the thermovision image, Figure (24-A), along an imaginary, horizontal line at the level of the nose. We note a gradual increase (whitening) in emissive intensity over the hair and up to the cheek region but then a sharp decrease occurs to nearby background at the nose which should be the whitest. In the VP-8 relief, this behavior is seen as a depression in the center of the face. The reason is, that as the degree of etching increases so as to correspond with the increasing relief structure of the reference face, a point is reached where enough metal is etched away that it begins to emit more like background, unetched metal. Thus, the correlation of emission with distance can be double-valued depending on the nature of the etched surface. This behavior could cause major difficulties for a hypothetical craftsman who might wish to utilize such a process to create a Shroud image. In addition, we noted that when heating the copper etching to temperatures sufficient to scorch cellulose, black oxide layers quickly and unavoidably developed causing variations in emissivity much larger than those due to etching. Further, when the hot etching was brought close to cloth, reaction products from the cloth often formed on the metal, masking the emissivity variations due to etching as viewed by the thermovision system. When the engravings were brought in contact with the filter paper thereby allowing heat conduction rather than thermal radiation to produce an image, the images were poor to the point of being unrecognizeable. For these reasons, along with other difficulties mentioned by Schwalbe and Rogers, we believe the engraving hypothesis can be rejected.

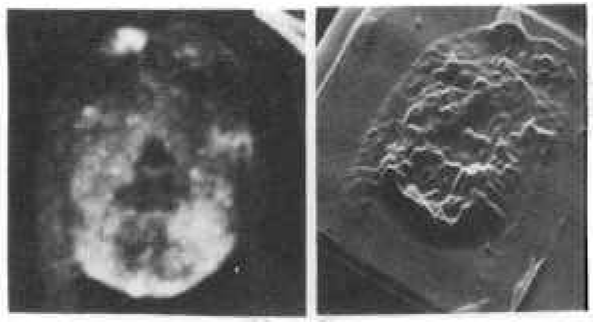

Figure 24. Engraving.
Moderate heating-No oxide formation

6. Electrostatic Imaging. As a final hypothesis category, we investigated the suggestion that electrostatic fields, possibly associated with lightning phenomena, caused a corona breakdown over a body surface whereby energetic electrons are guided by such fields and register thermal-like discolorations on the Shroud. It is beyond the scope of this paper to comment on the physical plausibility of this model, but the notion of electrostatic fields serving as guiding paths for charged particles as the carrier of distance information to the shroud seemed worth considering. In the discussion which follows, we do not consider the paths taken by charged particles but rather the electric field distributions under the assumption that image resolution and distance correlation can be no better than that which the field distributions will allow.

Let us assume that the body was lying horizontal in a vertical electric field and that the cloth merely intercepted the field lines. To model such a configuration, we coated a 1/4" plastic sheet with electrically conducting Television Tube Koat. We then attached a metallic profile shape of our reference face to the coated plastic with spray glue. At some distance above the face, we glued a horizontal metallic strip. We then applied several volts between the strip (which simulates a uniform electrostatic field) and the facial shape. The resulting current flows followed the field lines and we observed, as shown in Figure (25), the associated joule heating with the AGA-780 thermovision. We found that not only is distance a factor in field strength but probably even more important is local curvature of the body shape since electric field lines tend to accumulate around regions of curvature. Such an effect seems to be a potential problem with this type of action-at-a-distance mechanism inasmuch as the Shroud image appears to contain only distance type information.

Figure 25. Electrostatic Image Profile.

Thus, electrostatic imaging does not appear to be a viable way of producing an image like the one on the Shroud. In many respects, electrostatic images are like diffusion images because both obey Laplace's Equation for potential and number density respectively.

IV. CONCLUSIONS

In summary, we list the following conclusions resulting from our investigations of the Turin Shroud. We do not claim to have absolutely proven any of them (except the first) for reasons specified in the text, but we do believe them to have a high probability of being correct (independent of whether or not the Shroud is the actual burial cloth of Jesus.)

1. The frontal image on the Shroud has a shading structure consistent with a body shape covered with a naturally draping cloth and which can be derived from a single, global mapping function relating image shading with distance between these two surfaces. This interpretation would be a reasonable explanation for the Shroud image if a high resolution mechanism satisfying all image and chemical characteristics of the Shroud can be demonstrated.

2. The visible image on the Shroud is not the work of an artist in an eye/brain/hand coordination sense, nor does it appear to be the result of direct contact only, diffusion, radiation from a body shape or engraving, dabbing powder on a bas relief, or electrostatic imaging.

3. The visible image on the Shroud is probably not the result of a hot bas-relief impressed into cloth, but such a mechanism might be able to account for the Shroud image's distance correlation, resolution, and chemical structure; it does not seem to simultaneously account for the image residing on one side of the Shroud, low contrast of the Shroud image, or lateral distortions in the Shroud image (consistent with a draping cloth over a body shape.)

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