*Color Aerial Photography in Geologic Investigations**

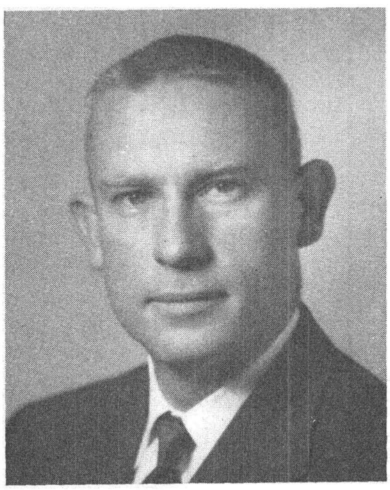
(Some Results of Recent Studies)

WILLIAM A. FISCHER,
U. S. Geological Survey, Washington 25, D. C.

ABSTRACT: *Color aerial photography provides geologic information not only through normal stereoscopic viewing procedures but also through certain color-measurement techniques. Although much geologic information is interpretable principally because of color differences in the photographic images distinguishable by the human eye, a greater potential for geologic interpretation may exist in the quantitative measure of color. Colorimeter measurements of light reflected from rock specimens indicate the part of the spectrum where the greatest tonal contrast may be expected, and thus narrow-band filters may be chosen for printing photographs on which subtle differences are enhanced. Color densitometer measurements of light transmitted through color transparencies may likewise reveal spectral data for increasing tonal contrast on black-and-white photographs. The tonal difference may represent different rock types or may represent similar rocks that have undergone different degrees of alteration. Distribution of rock units as well as certain structural data may be revealed through electronic enhancement of tonal contrast.*

INTRODUCTION

REPORTED here are some recent investigations of color measurement and interpretation of color aerial photography in geologic study. In addition to the application of what might be called normal subjective photo interpretation procedures, color-measurement techniques were used to obtain light-transmission and light-reflectance data that could be interpreted directly in terms of geologic significance, or that could be used for designing special black-and-white photography on which selected geologic information was emphasized. Only Aero Ektachrome transparencies and conventional black-and-white aerial photographs taken with a minus-blue filter were used in these studies. Other films or color photography resulting from additive color processes were not investigated.



WILLIAM A. FISCHER

SUBJECTIVE INTERPRETATION

Color aerial photography has many applications to photo interpretation, but some problems are more likely to be aided by color photography than others. In photo interpretation, the solution of problems involving variations in pattern or texture (to which color may contribute significantly), or problems involving color per se, is likely to be greatly facilitated by use of color aerial photography. On the other hand, color photography is not likely to be more useful than black-and-white for interpretive problems that relate largely to topographic configuration. Thus, for example, the total lengths of streams, which were delineated on the basis of topographic configuration, are shown on Figure 1 to be essentially the same

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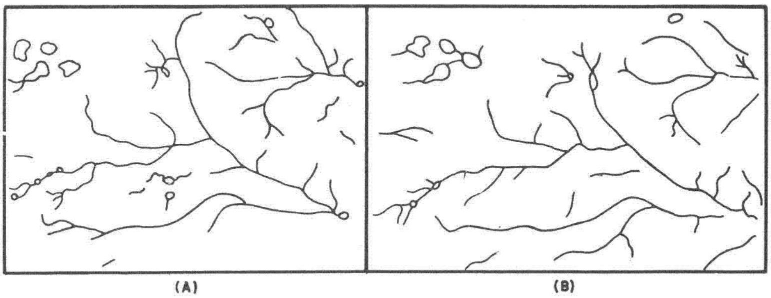

FIG. 1. Sketch showing similarity of total lengths of streams that could be mapped from conventional black-and-white photography (A) and from color photography (B) of same area in New Mexico.

for both color (Aero Ektachrome transparencies) and conventional black-and-white photography. Figure 2 shows in striking contrast the much greater total length of roads and trails that were recognizable on color aerial photography, principally because of color differences.

Recent study of a poorly vegetated semiarid area of east-central New Mexico showed color aerial photography to be particularly helpful in problems in geologic interpretation such as: (1) mapping the distribution of residual soils, (2) recognition of relic sink holes, and (3) determining the origin of drifting sand present on top of a limestone-capped mesa.

DISTRIBUTION OF RESIDUAL SOILS

Many areas in east-central New Mexico are overlain by a discontinuous and thin veneer of residual soils. In the area studied these residual soils are derived principally from limestone and sandstone. Not only do the limestone and sandstone photograph with similar tones on black-and-white photography, but soils derived from these rocks photograph with tones similar to the parent rocks. It is thus difficult to map the distribution of different residual soils from conventional black-and-white photography. On color aerial photographs, however, areas overlain by soils appear to have a smoother texture than the bedrock, and a delineation of soil and bare rock areas is generally made with little difficulty. Although textural differences commonly are the result of microrelief, which may be discernible on black-and-white photographs because of vertical exaggeration in the stereo model, here they are the result of color differences. The gray limestone bedrock is also distinguishable by color from the light-brown sandstone bedrock.

RELIC SINK HOLES

Numerous subcircular features in the valley floors are visible on color aerial photographs of the area studied. These subcircular features are not recognizable on black-and-white photography, and can be recognized on the ground only by the anomalous presence of a few scattered fragments of limestone. The recognition of these features as relic sink holes is geologically significant in supporting a concept of valley development by process of coalescing sink holes. Relic sink holes are commonly alined, and it is likely that they developed along master joints or faults which have in turn controlled the direction of stream flow. The relic sink holes are recognized on color aerial photographs because of differences in photographic textures. These tex-

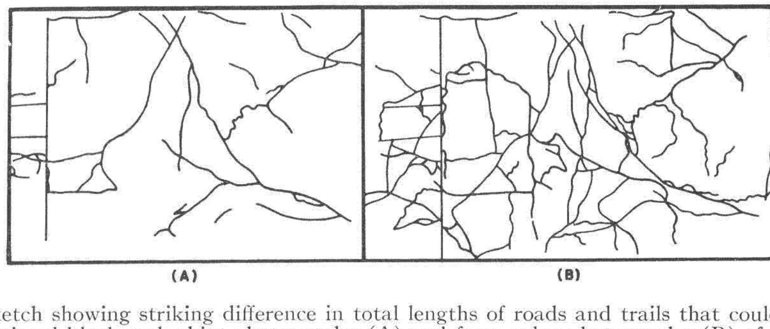

FIG. 2. Sketch showing striking difference in total lengths of roads and trails that could be mapped from conventional black-and-white photography (A) and from color photography (B) of same area in New Mexico.

FIG. 3. Conventional black-and-white photograph of an area in east-central New Mexico underlain by gray limestone and reddish siltstone. Contrast with figure 5.

tures probably result from subtle color differences that have insufficient contrast to be resolved as tone differences on black-and-white photography but which are of sufficient magnitude to be resolved as color differences on color aerial transparencies.

ORIGIN OF DRIFTING SAND ON LIMESTONE-CAPPED MESA

On black-and-white photography of the area studied, windblown sand is clearly recognized on a limestone-capped mesa, principally because of its dunelike topographic form, but there is no clue as to the source of the sand. On color photography, however, a trail of sand may be seen leading to the margin of a near-vertical 255-foot-high cliff, suggesting that the sand originated in the valley below and was blown up the side of the cliff by strong winds. Field examination showed the drifting sand to be mineralogically similar to rocks below the 255-foot cliff. Photographs of the area studied show the drifting sand with approximately the same gray tone as the residual soils on top of the mesa. The trail of sand leading to the edge of the cliff is thin, thus further diminishing any possible tone contrast that may exist between the sand and the residual soil. For this reason the thin trail of sand is not recognizable on black-and-white photography. The color difference between the windblown sand and the soil is much more marked, and color film is sufficiently sensitive to record the color contrast of even the thin veneer of the sand trail with the residual limestone soil.

COLOR MEASUREMENT

In addition to its demonstrated usefulness in a conventional interpretive sense, color aerial photography has great potential value as an intermediate product in preparing specially designed black-and-white photographs on which selected geologic data are emphasized, and as a source of direct quantitative information of geologic significance. Research to date in the geologic application of color measurement has been rather limited and there is much room for additional study. The results of some recent investigations of color measurement as applied to geology are described below.

COLOR PHOTOGRAPHY AS INTERMEDIATE PRODUCT

In an area in east-central New Mexico, a thin reddish-colored siltstone and an underlying gray limestone were found to be essentially indistinguishable on conventional black-and-white aerial photographs (Figure 3). The contact of the siltstone with the underlying limestone is not readily traced even on color aerial photographs, despite the apparent strong color difference. Field mapping is time-consuming because the reddish-colored siltstone is a thin formation and crops out over much of the topographic surface, which is dissected and uneven. In an attempt to facilitate mapping the distribution of these two rocks, spectral reflectance measurements were made of rock samples representative of the colors of the formations in the field. Colorimeter measurements were then contrasted to determine the part of the spectrum which showed the greatest difference in total reflection of light for the samples in question. In this instance the greatest contrast was in the 450–520 millimicron range (Figure 4, units *B*

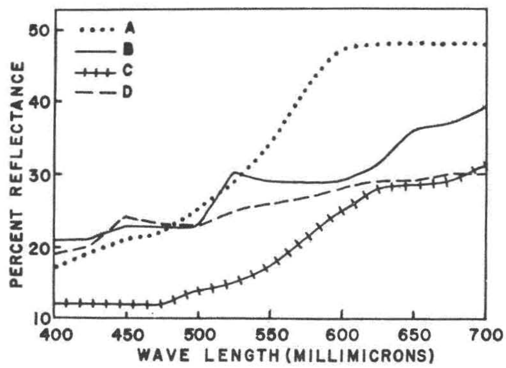

FIG. 4. Spectral reflectance curves of fresh samples of light-brown sandstone (A); gray limestone (B); red shaly siltstone (C); and gray sandstone (D).

and *C*). Photographs of rock samples on panchromatic film through filters which transmit only that part of the spectrum verified the significance of color measurements, and showed strikingly that two rocks of similar appearance on conventional aerial photography might be easily differentiated when selected wave-length photography was used (see also Ray and Fischer, 1960, p. 147, Figure 5, and Fischer, 1960, p. B-138, Figure 61.2). A black-and-white print was then made from the color aerial transparency, using panchromatic film and the selected filter used in photographing the rock samples. The increased tonal contrasts of the different rock units are shown in Figure 5.

A somewhat similar procedure was used to differentiate hydrothermally altered volcanic rocks of an area in Nevada. Color measurements were made directly from the color transparency rather than from rock samples. Field investigation, study of color photography, and petrographic examination had disclosed that the lithology of relatively unaltered rocks could be recognized by color on color photographs. In addition the degree of hydrothermal alteration could also be correlated with color. Red color appeared to increase with the intensity of alteration. It was also found, however, that highly altered rocks reflected approximately the same amount of red light as some bright unaltered rocks, but that, in contrast, they reflected much less blue light than fresh rocks. Therefore a black-and-white negative was made from the color transparency using a filter that transmitted only blue light. A film positive made from this negative was then placed in an image-enhancing device through the cooperation of the U. S. Naval Photographic Interpretation Center. (This device permits enhancement of minor gray tone differences and electronically outlines all parts of a photograph having the same tone value.) The enhanced image was observed and rephotographed at three settings of the instrument. At the first setting areas believed to be the most intensely altered (the darkest gray tones) were outlined electronically (Figure 6A). Rocks thought to be in an intermediate stage of alteration (intermediate tones) were outlined at the second setting (Figure 6B). At the third setting (Figure 6C) rocks considered to be relatively unaltered (lightest gray tones) were outlined. Although further field studies will be required to verify

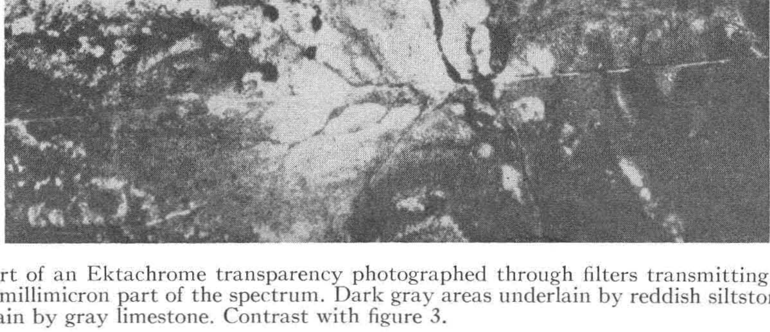

FIG. 5. Part of an Ektachrome transparency photographed through filters transmitting only light in the 450–520 millimicron part of the spectrum. Dark gray areas underlain by reddish siltstone; light gray areas underlain by gray limestone. Contrast with figure 3.

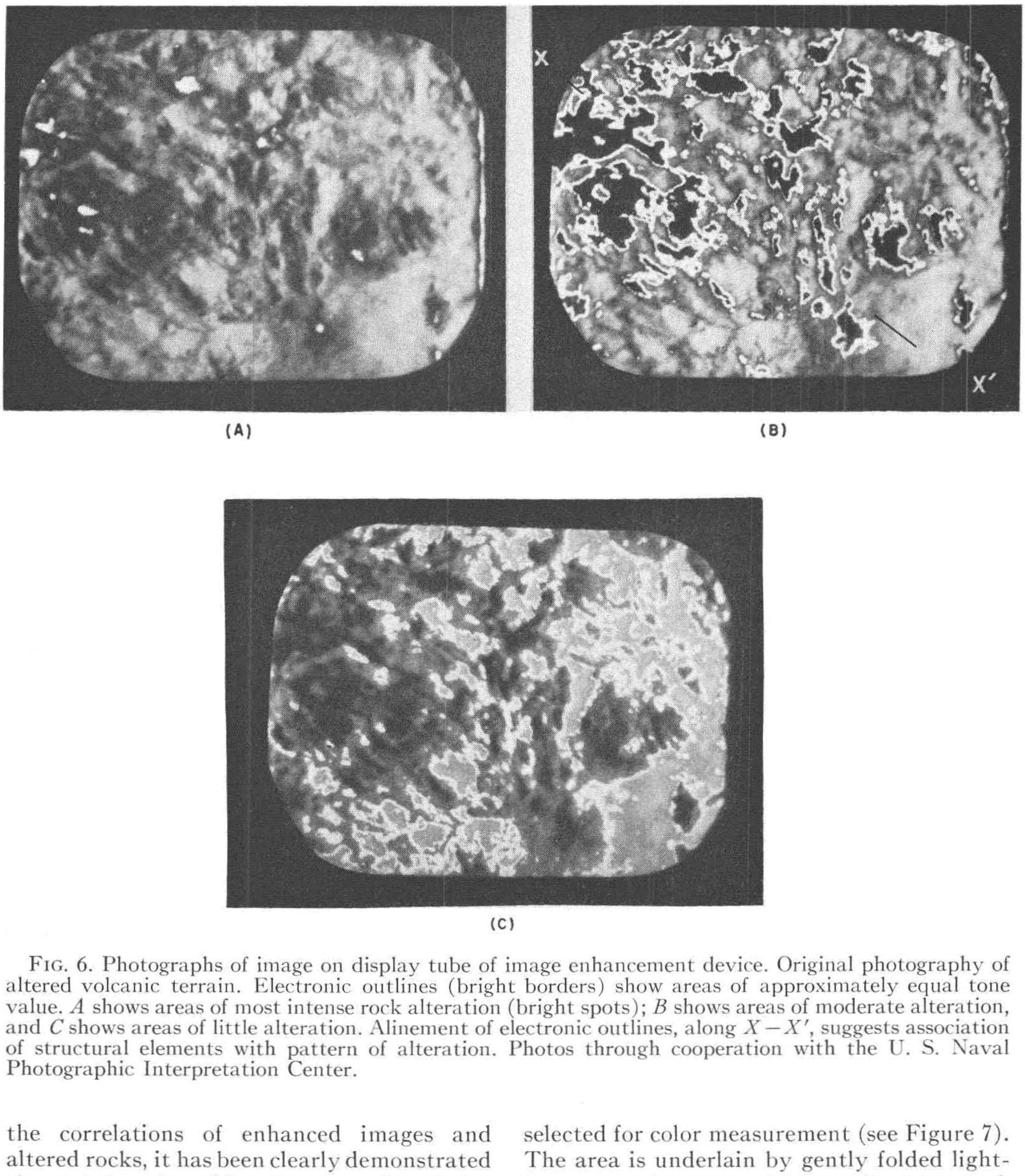

FIG. 6. Photographs of image on display tube of image enhancement device. Original photography of altered volcanic terrain. Electronic outlines (bright borders) show areas of approximately equal tone value. *A* shows areas of most intense rock alteration (bright spots); *B* shows areas of moderate alteration, and *C* shows areas of little alteration. Alinement of electronic outlines, along $X-X'$, suggests association of structural elements with pattern of alteration. Photos through cooperation with the U. S. Naval Photographic Interpretation Center.

the correlations of enhanced images and altered rocks, it has been clearly demonstrated that subtle color differences on color photographs can be enhanced by printing specially designed black-and-white copies and employing image-enhancement techniques for viewing the black-and-white duplicate. It has also been shown that parts of the original color photograph having similar color characteristics can be outlined electronically.

COLOR AS SOURCE OF DIRECT QUANTITATIVE INFORMATION

In order to test color aerial photography as a source of direct quantitative measurements that might be geologically significant, an area of poorly exposed rocks in New Mexico was selected for color measurement (see Figure 7). The area is underlain by gently folded light-brown sandstone and gray limestone. A traverse at right-angles to the structural trend was made across the color transparency of the area by means of a color densitometer. The traverse was made three times along the same line, once recording the amount of red light, once green light, and once blue light passing through the transparency. Previous colorimetric measurements on rock samples had indicated that significant differences in amounts of reflected light could be expected. Superposition of the color records showed divergence of the red and blue records to be especially strong (see Figure 8, *X-X′*). Areas underlain by sandstone were marked on the

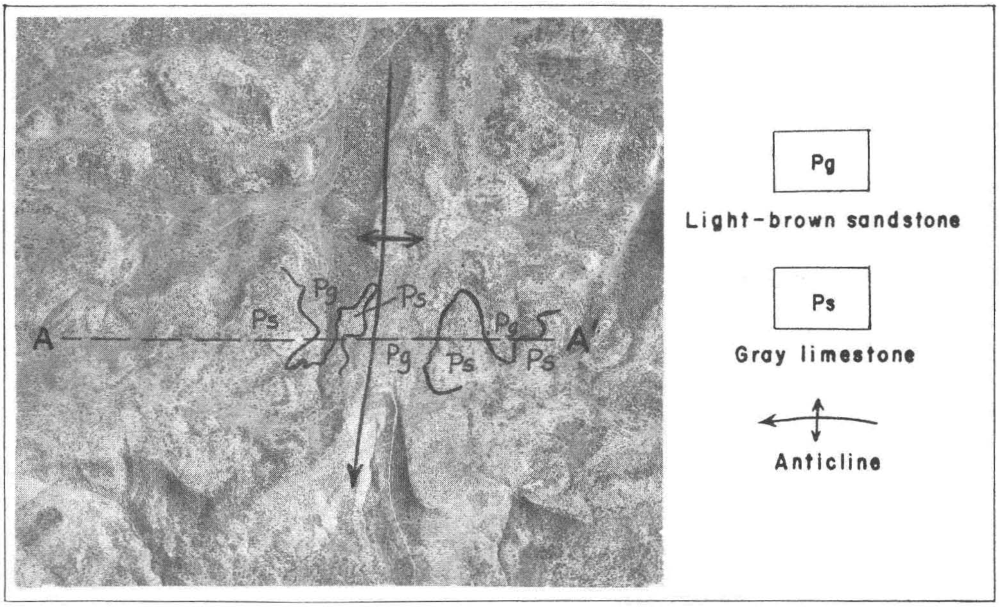

FIG. 7. Conventional black-and-white photograph of an area in east-central New Mexico underlain by light-brown sandstone and gray limestone. Line $A-A'$ marks location of color densitometer traverse (see fig. 8).

combined color record by a sharp increase in the amount of red light that passed through the color transparency and a related decrease in the amount of blue light transmitted. Impingement points of the red and blue records tend to occur at the contacts of sandstone with limestone. The geologic contacts between the sandstone and limestone thus might be positioned by measuring the relative amounts of red and blue light transmitted through the color aerial transparency.

Using arbitrary units, the per cent difference between the red and blue records was also computed and plotted at numerous points alone the original traverse line (Figure 8, Y-Y'). The per cent difference between red and blue light increased along the traverse as the structural axis was approached and was greatest over the axis (Figure 8, Y-Y'). The greater reflection of red light from the sandstone over the axis of the anticline may relate to a greater oxidation of iron minerals along the structurally high area where the water table would be depressed relative to the flanks

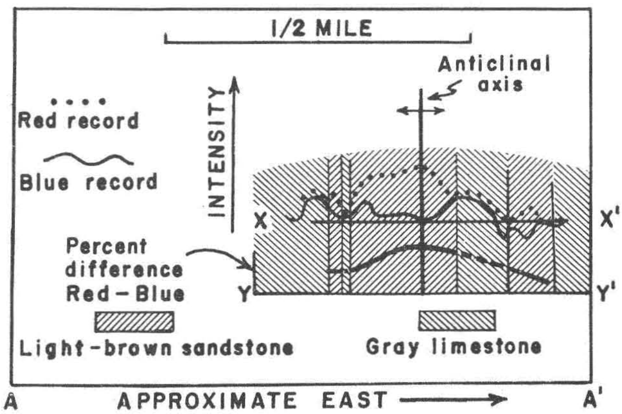

FIG. 8. Chart showing relative amounts of red and blue light passing through color transparency along part of line $A-A'$ of Figure 7. $X-X'$ shows relative amounts of red and blue light referenced to a fixed transmission value. $Y-Y'$ shows relative amounts of red and blue light expressed as per cent difference and referenced to the position of anticlinal axis.

of the structure. But whatever the cause of this difference in reflection, colorimetric methods would appear to be of help in structural studies, particularly in areas of poor outcrop.

Conclusion

Color aerial photographs almost always contain geologic information that is not recorded on conventional black-and-white aerial photography. Recent investigations, reported in part herein, have convinced the author that, while subjective photo interpretation procedures may well provide significant geologic information from color aerial photographs, a quantitative approach to photo interpretation studies may ultimately be the most rewarding.

References

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*Surface Roughness of the Moon**

H. S. HAYRE,
Electrical Engineering Dept.
Univ. of New Mexico

In recent years considerable interest has been aroused in the radar determination of the order of surface roughness of planetary bodies. In particular, quite a few attempts (Evans 1960, Hayre 1961, Hughes 1960, Leadabrand 1960, Pettengill 1960) have been made recently using the results of monostatic and bistatic radar reception of lunar echoes, to determine the roughness of the visible lunar surface. Senior and Siegel (1960) suggest a quasi-smooth moon at radar frequencies while Leadabrand et al. (1960) state that the central portion of the visible lunar surface up to approximately 600 μ sec-radar depth is quasi-smooth, while the outer areas up to the limbs are rough. Evans (1960 a) shows that approximately 50% of return power is returned from first 50 micro-second depth (0.1 radius of the moon), and therefore the central part of the moon must be smooth while the outer areas are said to obey Lambert's scattering law. In this article, Davies-Moore-Hayre (1961) Model is used to estimate the lunar surface roughness.

A study of some recent moon echo results (Evans 1960 and 1961. Pettengill 1960) seems to suggest that it may be necessary to analyze the variation of radar scattering cross-section with the angle of incidence (θ) in three different ranges. This is necessitated because small changes in θ correspond to very large changes in distance from the center of the moon surface. The angle of incidence varies from zero to ninety degrees as the the angle subtended at the earth based receiver by an annular area on the moon varies from zero to seventeen minutes, and the corresponding radius from the center of the visible surface to the illuminated area changes from zero to the radius of the moon. This would then imply that one would associate different roughness characteristics with each range of angles as discussed later in this article.

Various models have so far been used to predict the roughness of the target terrain from the radar return data. The Davies-Moore-Hayre Model (Hayre and Moore 1961) uses the experimental autocovariance of the elevations and their probability density function, in applying the Kirchhoff-Huygens' principle. Certain assumptions about perfect conductivity, isotropic scatterers, near-vertical incidence and no part of the terrain being shadowed by any other part, etc. were employed. Contour maps were used to calculate the autocovariance functions. This resulted in the following expression for the radar scattering cross-section.

$$\sigma_0 = (4\sqrt{2}\,\pi B^2/\lambda^2)(\theta \cos^2\theta/\sin\theta) \exp(-4k^2\sigma^2\cos^2\theta) \cdot \sum_{n=1}^{\alpha} (4k^2\sigma^2\cos^2\theta)^n \cdot [(n-1)!(2B^2k^2\sin^2\theta + n^2)^{3/2}]^{-1} \quad (1)$$

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