

A DIGITAL FILE OF THE LUNAR NORMAL ALBEDO

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Abstract. A digital file of the normal albedo of the Moon has been produced at a resolution of about 1/550 of a lunar diameter (about 6.3 km). The file was produced from five photographs taken with the 61-cm reflector of the Northern Arizona University Astrophysical Observatory. No mosaicking was necessary. Spatial control is selenodetic rather than landmark-morphologic. Photometric control is provided through a combination of electrography and regular photoelectric photometry. Pixel photometric function corrections are employed. The file was provided as data base for the Lunar Consortium. Brief discussion of the scientific implications of the frequency histogram is offered, and the negligibility of lunar limb darkening below $\varepsilon = 77^\circ$ is affirmed. It is specifically desired not to withhold these data from publication while more significant and detailed scientific interpretation is carried on.

1. Introduction

The history of lunar astronomy has demonstrated the significance of photometry of sunlight scattered from the surface of the Moon in a wide variety of ways. The contrast with both the land provinces of the Earth and most laboratory-contrived surfaces is such that even the uncalibrated eye can detect the tremendous increase in brightness as the configuration of illumination-observation approaches zero phase-angle. The insignificance of lighting-viewing configuration for back-scattered radiation at Full Moon coupled with a distinct Sun-altitude dependence at other phases is also obvious. It has been 13 yr since the last major review of lunar photometry (Minnaert, 1961). During that time the dominance in Earth-based studies has shifted from the photographic to the photoelectric investigative technique (Willey and Pohn, 1964; Gehrels *et al.*, 1964) for reasons of precision and accuracy. Photographic photometry has been employed because of its higher data-storage capacity, such as was required for the production of a comprehensive map of the normal albedo of the Moon (Willey, 1974; Pohn and Willey, 1970). Even in this case, photoelectric calibration of not only the zero point but also the shape of the H and D curve through simultaneous observations of selected lunar features spanning its dynamic range of surface brightness has been retained.

Normal albedo was one of the earliest devices with which the distinctness of separation of the near-face of the Moon into a variety of geologic formations was achieved. The major correlation of albedo with age on a two-family basis, the terrae and the maria, achieved through combination with the mapping tools of surficial expression and crater density, remains a useful generalization after the completion of the Apollo exploration, even though established before the first Ranger photographs were obtained. The now existent maps of the normal albedo of the Moon were produced primarily for this scientific purpose. It is also worth mentioning

on the engineering side that the Lunar Orbiter Program, the only comprehensive lunar photographic mapping program at space-borne resolution that has yet been undertaken, was dependent on a preliminary version of the first map for the implementation of proper exposure settings.

Since Apollo 17, an appreciation of the difficulties associated with the comprehensive correlation of now-many dimensions of data types, differing greatly in resolution and coverage, has led to the formation of the Lunar Consortium research program, specifically chartered for the purpose of carrying out this data integration. It is bound together in part by parallel research efforts in the methodology of digital image-processing. Such an effort is clearly directed toward the improvement of correlation-detection. But it is also intended to serve as a means of harmonizing the differences between investigative techniques of individual researchers in this highly interdisciplinary program. As a part of the Lunar Consortium, the digitization of lunar albedo data was undertaken.

There are several reasons why the desired digital albedo file was better carried out as an astronomically new program, rather than through the digitization of the pre existing map (Pohn and Wildey, 1970) at 1 : 1000000. (1) A resolution of about $\frac{1}{600}$ of a lunar diameter was the most that could be accommodated by the digital computer assigned to the Consortium (the PDP-11/45 of the Flagstaff Computation Branch of the U.S. Geological Survey) and was also compatible with the resolution of the majority of data-types of the program. (2) Because of problems of mosaic-control, position finding on the pre-existing map is not possible exclusively through the use of a selenographic grid, but is in part landmark-dependent, requiring the users capacity for pattern recognition. (3) A human operator, rather than a machine, would be required to digitize the map, which is more time consuming than carrying out a fresh observation program digitally oriented from the start, especially considering the complication inherent in resolution-matching without the introduction of aliasing errors. (4) The pre existing map is not a map of 'true' normal albedo. Any observed lunar image requires selenographically variable photometric function corrections in order to produce such a result. Thus the photographic plate used in producing the map possesses a narrow but non-vanishing continuum of lunar phase-angle. For a map of such resolution, especially at the time it was compiled, the processing limitations necessitated a blanket phase-correction to the entire lunar face. Even this had to be carried out prior to Apollo derived knowledge of the eclipsed region of the domain of the lunar photometric function (Wildey, 1973; Wildey and Pohn, 1969; Pohn *et al.*, 1969), and therefore required an extrapolation of observations to zero phase-angle. Such a restriction does not apply to the present study on either count.

2. The Observations

2.1. SPATIAL ADAPTATION

It was desired to collect the photographic data in such a manner that the selected digital interval and slit-size would not introduce aliasing errors, i.e., would not violate the Nyquist criterion. Moreover, the possible values of the formatting parameters of the Joyce-Loebl Beckmann-Whitley isodensitracer, which was to do

the digitizing, had to be taken into account. In the second regard, the plate-scale at the $f4.5$ Newtonian focus of the 24 inch (61 cm) telescope of Northern Arizona University Astrophysical Observatory, enabled a digitizing of the entire lunar image (avoidance of mosaicking the isodensitracings) with 550 pixels per lunar diameter. The first point is worth slight elaboration. Intervening between the true variation of brightness over the lunar surface and the digital file are the three successive convolutions produced by the turbulent refractive fluctuations of the atmosphere, the diffraction due to the finite aperture of the telescope, and the integrating area of a small square slit on the isodensitracer. It is the resulting two-dimensional continuous output function that is sampled at the discrete points of a two-dimensional matrix. In terms of the Fourier transforms of input and output analog data we have the simpler view of a product of successive transfer functions rather than convolutions of point-spread functions. When the output function is sampled at regular discrete points, the Fourier transform of the resultant bears the following relation to the Fourier transform of the continuous function. It is the Fourier transform of the continuous function produced not only at the origin in the spatial-frequency domain but also zero-point shifted to lie at the fundamental and all harmonics in spatial-frequency of the sampling cycle. It is therefore clear that a one-to-one correspondence between the digital record and the continuous record of which it is a sample cannot exist unless the set of shifted Fourier transforms do not overlap. Only in that way can the lowest order, whose inverse is the continuous function that was sampled, actually become isolated and accessible information. The optical transfer function of a perfectly figured mirror in incoherent light is simply the auto convolution of its pupil function as an area-wise step-function, properly scaled to units of spatial frequency for the image through the wavelength of light and the focal length of the mirror. It was therefore necessary to use an off-axis diaphragm resulting in a telescope aperture of 1.5 cm (!) in order to guarantee a spatial-frequency cut-off of one-half the pre-selected sampling frequency.

Prior to the above step, the consideration arises as to the possibility of introducing spurious trends in the data while yet in analog form through the use of too wide an aperture in the isodensitracer. Contrary to widespread belief, as small a sampling aperture as is possible, consistent with grain noise levels, and not the one which succeeds in abutting the sampled areas, is optimum. This is true, provided the other aforementioned criterion for the apodization cut-off has been observed. The transfer function of a square scanning aperture is $(\sin \omega_x \sin \omega_y)/(\omega_x \omega_y)$, except for an effect of the dynamic non-linearity of the photographic emulsion (intermodulation and harmonic distortion). The scaling is such that $\omega_x = \omega_y = \pi$ corresponds to half the length of a side of the scanning aperture. Such a transfer function can be seen to possess 'side-bands', non-zero values at well above the frequency of the basic spatial cycle that fits in the slit. When using a controlled spatial frequency cut-off in the spatial spectrum of the data being operated on, so that no information is sensed through the side-bands, it is clearly optimum to have the above transfer function utilized in the range where the approximation $\sin \omega/\omega \sim \omega/\omega = 1$ is valid. The 'abuttment' criterion implies a spatial amplitude attenuation of $2/\pi$ at the limiting spatial frequency of the information spectrum. Of course, if no thought has been

given to later digitizing and it has been thought that an effective limiting of resolution can be imposed on a high resolution photograph simply by widening the densitometer aperture (not true!), the high spatial frequencies will not actually be lost but will be re-weighted in a complicated way with selective phase-shifting by a half cycle. The effect is analogous to taking out of focus images, which is also an undesirable method of degrading resolution. More detailed considerations of these and related effects in regard to other problems in astronomical photography have been offered in earlier papers (e.g., Wildey, 1967, 1973). In the present effort, we have digitized with a densitometer aperture of one-fourth the sampling interval.

2.2. THE PHOTOGRAPHIC PHOTOMETRY

On the Greenwich data of November 29, 1974, between 10^h and 12^h19^m U.T. (a penumbral eclipse began at 12^h25^m), a total of nine plates were exposed under conditions that would guarantee a minimal correction of the photometry to zero phase-angle. The sky was cloudless and astronomical-seeing was entirely adequate for the resolution desired. Eastman-Kodak IIA-E emulsion through a Wratten 4 filter was employed to approximate the effective wavelength of the Johnson-V band pass. Although such an approximation would be inadequate for photometry on a wide variety of stars, the coloration shown by the Moon is quite limited (McCord, 1969) and such a degree of mismatch is inconsequential (Wildey, 1974). Exposure times ranged from 1 to 4 s. The variation was in part intended to ensure the detection of any failure to properly represent the possible non-linearities in the *H* and *D* curves in the later digital data reduction procedures. With the telescope diaphragmed to 1.5 cm, and operating at the Newtonian focus, it was simple to set exposure duration with a hand operated flap over the telescope aperture, rather than via the plate-holder slide. Thus photometric precision did not depend on the uniformity of a focalplane shutter. Nor was 1 s so short that the period of partial aperture coverage could significantly affect the optical transfer function. The plates (2" × 2") were developed together for 5 min in UFG using a Mount Wilson and Palomar type rotating and rocking developing tray to ensure uniformity of development. This was followed by rapid application of short-stop acetic acid bath. The five best plates were used to produce the albedo file.

2.3. PHOTOELECTRIC CALIBRATION OF PHOTOMETRY THROUGH THE KRON ELECTRONIC CAMERA

From an independent study of the lunar photometric function presently being carried out by Ables and Wildey (private communication), an electrogram of the full Moon at even lower resolution ($\frac{1}{125}$ the lunar diameter) was available. This was taken with the Kron Electronic Camera. A photoelectric calibration could therefore be obtained using the rigorous proportionality between optical density and focal-plane flux characteristic of this device. The particle-track emulsion plates used with the electronic camera are also of extreme uniformity. The camera has been described in detail in Kron (1966). The radiation bandpass of the electrogram is more nearly equivalent to the combined Johnson *B* and *V* bandpasses. But since as the entire set of pixel-to-pixel correspondences between the electrogram and the photography was used to obtain the calibration curve, and since no overall systematic relation

exists between normal albedo and color (Willey and Pohn, 1964), the mismatch of photographic and electrographic bandpasses presents no problems even though provision for finding a color equation was not included. The use of such a large number (approximately 9000) of data points also insures the averaging out of any residual variations in the quantum efficiency of the photocathode imaging surface.

In the calibration process it was first necessary to find the multiplication factor reducing the density file from the electrogram (or electronogram) to a product of normal albedo and photometric function. Although this was done directly from the Pogson magnitude difference between the Sun and the full Moon, it was done indirectly through the previous U.S.G.S. lunar albedo map. That map was used in combination with the electrogram to revise the geometric albedo of the Moon by obtaining a very accurate average of the normal albedo. The magnitude of the true-full-Moon (in transparent eclipse) was then evaluated for mean Sun-Earth-Moon distances as previously reported (Willey, 1976). Individual selenographic photometric function corrections were applied. The electrographic file was then corrected to normal albedo by applying the above-derived factor and also the appropriate Heiligenschein correction based on the applicable angles of phase, incidence, and emergence (Willey, 1976).

Two methods have been used to obtain the conversion of density values in a given photographic file. Both involve the same procedures in spherical astronomy, differing only in the formation of the relation between optical density of the photographic plate and the product of normal albedo and photometric function. In the first approach, an analytical form for the H and D curve was assumed; namely,

$$\begin{aligned} \log(\rho\Phi) = & A_1 + A_2 D + A_3 D^2 + A_4 D^3 + A_5 \log(D - D_f) \\ & + A_6 \log(D_s - D). \end{aligned} \quad (1)$$

The values D_s and D_f represent crude estimates of the chemical fog and the saturation density, respectively. Only the coefficient vector A_j is evaluated from the least-square procedure. In the selenographic correspondences for comparison of two photometric data, the photographic density file was accessed at every fifth pixel of every fifth line. Those points within the lunar image were combined with the adjacent eight pixels of a cubic lattice to form a mean. In an effort to produce a density corresponding to the average luminance rather than an average density, conversions were made and the mean was inverted using the manufacturers nominal H and D curve and assuming operation on its linear portion. This can only be an improvement over a straight mean-density, even if the actual H and D curve is far from nominal. Actually, with the use of so many data, this step of attempting to correct for differences in resolution between the electrographic and photographic files might not be crucial, but it makes the residuals more indicative of actual precision. A gaussian-weighted average would have been preferable to the '2-dimensional box-car' described above, but it would have meant extending the range of file-sampling in this innermost convolution with an excessive increase in computation time. With the production of this basic photometric datum from the photographic file, a three-dimensional transformation of coordinates was performed to obtain the corresponding $\rho\Phi$ by double interpolation in the electrographic file.

Using the computed lighting geometry for both the electrographic and photographic data at the computed selenographic coordinates, and in the Heiligenschein region of the photometric function, the value of $\rho\Phi$ was corrected to correspond to the photographic file.

A second approach to the H and D curve was made by dividing the 168 digital sample range of the isodensitracer, with regard to the photographic file, into 36 linear ranges with overall mathematical continuity. Rather than carrying out 36 constrained least square fits to linear functions, the average values of $\log(\rho\Phi - \text{corrected})$ and D that fell in a particular pigeonhole, were evaluated. Upon determining the particular pair of pigeonholes, j and $j + 1$, which bracketed a density value D , the resulting double-table was used according to the interpolation formula

$$\log(\rho\Phi') = [\log(\rho\Phi')]_j + \{[\log(\rho\Phi')]_{j+1} - [\log(\rho\Phi')]_j\} \\ (D - D_j)/(D_{j+1} - D_j). \quad (2)$$

Any extrapolation involving the tabular approach was linear using either of the extreme pairs of pigeonholes, whereas the analytical approach involved no alteration of the derived formula when used in extrapolation of the data. In any event, the average residual between the reduced electrographic file and the reduced photographic file for the two approaches agreed within several percent. Neither method possessed a consistent advantage for any of the plates. The residuals for individual plate calibrations are shown in Table I. Although Heiligenschein corrections have been made, corrections for resolution differences have not. True precision is therefore better than indicated.

TABLE I

Mean intercalibration residuals
– electronography to photography

Plate number	RMS residual (albedo units)
N3W	0.0060
N4W	0.0064
N7W	0.0073
N8W	0.0069
N9W	0.0098

It may be objected that the H and D curve found in the foregoing manner cannot be correct at the extreme ends because of the differences in resolution between the electrogram and the photographs. To investigate this further, a histogram of the frequency distribution of normal albedo was obtained from a preliminary result. As shown in Figure 1, the curve drops steeply to zero at the faint end but has a definite foot on the bright end. We therefore added ten additional brightest points from our previous albedo map, corrected according to the supplement. With input normal albedo and selenographic coordinates, the photographic

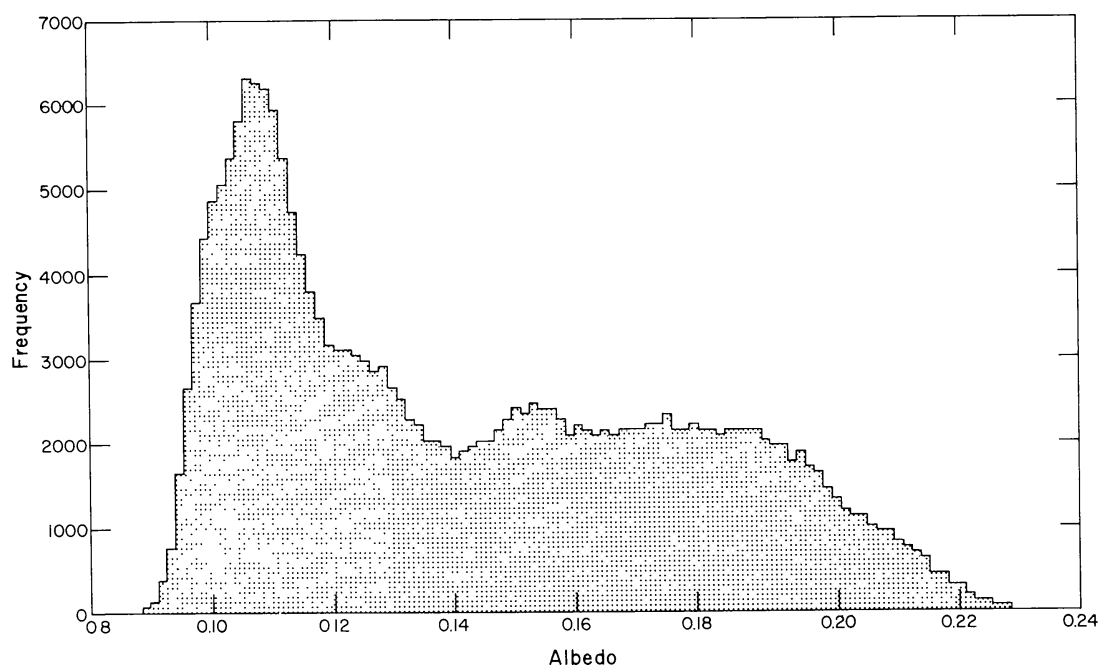


Fig. 1. Frequency histogram for the normal albedo of the Moon as observed in the present investigation.

density file was searched for a maximum value in a 10-by-10 pixel region surrounding each transformed point. These additional lighting-corrected correspondences were entered into the least-square procedure.

2.4. THE FINAL PHOTOMETRIC OUTPUT

The available core of the PDP-11/45 is inadequate to store either of the above image files. Only one TV line from each file is in core at any one time. Even then, only one or a few pixel brightnesses from that line may be processed while it is actually in core. The whole files as used in the above processing are disk-files. A magnetic tape file is finally created for each photographic plate that is reduced, and, from this five-image tape file, a master mean file is produced. The output file from individual plate reductions is in the form of an orthographic projection at mean libration, so that a corresponding selenographic grid has straight-line latitude projections. Individual output files are such that a lunar diameter just fills the available 596×596 array; the individual tape records, however, are half-a-line at a time. As each pixel in the output file is sequenced, its coordinates are transformed to the libration of the photographic density file. The result is rounded off to the nearest pixel in that file and the density accessed. (It was determined that the double-interpolation originally planned would have increased computation time to approximately 30 hr per plate.) The density is converted to $\rho\Phi'$ and then corrected to ρ using the standard Heiligenschein region of the photometric function.

Actually, the five image tape file described is three dimensional rather than two. The non-spatial dimension corresponds to the identification of which of the five photographic plates has produced the normal albedo value. Adjacent sets of five pixels are normal albedos for the same point and, ideally, agree in value. Thus, except for the first file produced, a tape record is read into core representing cumulative processing through the preceding plate. The appropriately located words in the

five-deep TV half-line are replaced with newly computed values of normal albedo. The augmented record is then written on a second tape. Unless the tape just written is produced at the reduction of the fifth plate, it will be read when the next photographic file is reduced.

In producing the master-mean file, each set of values of normal albedo is examined in sequence as read from the five-image tape. First, bit-errors and gross plate defects are discriminated against on the basis of zero, negative, or excessive (in excess of 100%) values of normal albedo. A statistical discrimination against the remaining values proceeds as follows. Three quantities are computed for each value of normal albedo: (1) a mean value from a set in which it is excluded, (2) an average deviation for the other values wherein they are individually differenced from averages for which they were similarly individually excluded, and (3) the individual value's own deviation from the first computed mean. When the quantity produced in step 3 exceeds three times the quantity produced in step 2, the individual normal albedo is excluded from the set designated for final averaging. Only one such cycle is allowed. The mean of the values in the final set is computed and also the standard-deviation-of-the-mean. From the pixel coordinates, selenographic longitude and latitude are computed, and four adjacent words are formed in the output array consisting of λ , β , ρ , and S.D. The master-mean file is thus also three dimensional, is put out a half-line at a time, and is of course still an orthographic projection at mean libration, just filling the square array. The standardized Mercator projection of the Lunar Consortium has also been filled from this master-mean file.

2.5. THE ASSOCIATED SPHERICAL ASTRONOMY

Some of the mathematical formulae we have used have been derived elsewhere (Willey, 1973). In those instances, only the final results will be shown.

The first major operation in the category of spherical astronomy is the determination of transformations from pixel coordinates to selenographic coordinates, which implicitly provides, thereby, transformation between pixel coordinates in the photograph to pixel coordinates in the electrogram. The processing is completely hands-off when star trails are obtained by slowing the guide rate of the telescope and then digitizing with raster lines parallel to the star trails. A set of data points is first obtained to represent pixel coordinates of the lunar limb. This is done by finding the value of X on each TV line (integer value of Y) for which the down-line component of the density gradient is a maximum. A parabola is fitted to the three highest values and its analytical maximum gives the limb value of x for a given value of y to a fraction of a pixel.

With this set of limb points, a radius and center coordinates are found by a least-square fitting to the equation for a circle. Two rejection cycles were permitted for data whose residuals exceeded standard deviation by a factor of 2.5. A transformation matrix and its inverse was next computed from data interpolated from the ephemeris. The geocentric libration parameters were converted to topocentric values, from which emerged the transformation matrix from selenographic cartesian coordinates to the cartesian system corresponding to the TV raster matrix elements and line-of-sight, shifted in origin to the center of the lunar face,

$$\begin{pmatrix} -\cos l'_{\oplus} \cos C', & \cos l'_{\oplus} \sin C', & -\sin l'_{\oplus} \\ [\sin l'_{\oplus} \sin b'_{\oplus} \cos C' & [-\sin l'_{\oplus} \sin b'_{\oplus} \sin C' & -\cos l'_{\oplus} \sin b'_{\oplus} \\ +\cos b'_{\oplus} \sin C'] & +\cos b'_{\oplus} \cos C'] & \\ [-\sin l' \cos b'_{\oplus} \cos C' & [\sin l' \cos b'_{\oplus} \sin C' & \cos l'_{\oplus} \cos b'_{\oplus} \\ +\sin b'_{\oplus} \sin C'] & +\sin b'_{\oplus} \cos C'] & \end{pmatrix} \quad (3)$$

A residual transformation, originally in the form of a pure rotational transformation about the line-of-sight, was next determined on the basis of observed pixel coordinates of features of known selenographic coordinates from a digital image display. It was found necessary to relax strict orthonormality in the form of an allowance for an assymmetric scale adjustment in the TV frame coordinates because of inequality of the horizontal and vertical sample spacing in the IDT output (Kell factor not unity). The assymetry amounted to about 6%. In carrying this out, the Moon was considered to be spherical in the selenographic-cartesian system, with a radius in pixels equal to the value determined in the aforementioned manner, and ellipsoidal in those cartesian systems with a TV raster subspace insofar as selenocentric angles were required to agree for the same landmarks in all systems. The additional transformation matrix required to right-multiply the foregoing transformation matrix is, therefore, of the form

$$\begin{pmatrix} A_{11}r_x, & A_{12}r_x, & 0 \\ A_{12}r_y, & -A_{11}r_y, & 0 \\ 0, & 0, & 1 \end{pmatrix}. \quad (4)$$

The transformation was worked out to include a reflection of one of the axes, as shown above, the reason for which need not concern us here. Using a set of 15 selenographic standards, their selenographic coordinates (angular) were used to determine their selenographic-cartesian coordinates

$$\begin{pmatrix} R \cos \beta_j \sin \lambda_j \\ R \sin \beta_j \\ R \cos \beta_j \cos \lambda_j \end{pmatrix} \quad (5)$$

Using the transformation matrix deduced from the ephemerides, we obtain a set of partially transformed vectors to be operated on by the residual matrix. It was the sum of the squares of vector differences between the resulting predictions and the observed pixel coordinates, in two dimensions only, that was to be minimized. After slight reduction, the implications of the vanishing of the appropriate partial derivatives is

$$\begin{aligned} & \left(\sum_j x_j^2 \right) A_{11} r_x^2 + \left(\sum_j y_j^2 \right) A_{11} r_y^2 + \left(\sum_j x_j y_j \right) r_x^2 A_{12} \\ & - \left(\sum_j x_j y_j \right) r_y^2 A_{12} - \left(\sum_j x_j x'_j \right) r_x + \left(\sum_j y_j y'_j \right) r_y = 0, \end{aligned} \quad (6)$$

$$\begin{aligned} & \left(\sum_j x_j y_j \right) r_x^2 A_{11} - \left(\sum_j x_j y_j \right) r_y^2 A_{11} + \left(\sum_j y_j^2 \right) r_x^2 A_{12} \\ & + \left(\sum_j x_j^2 \right) r_y^2 A_{12} - \left(\sum_j y_j x_j' \right) r_x - \left(\sum_j x_j y_j' \right) r_y = 0, \end{aligned} \quad (7)$$

$$\begin{aligned} & \left(\sum_j x_j^2 \right) r_x A_{11}^2 + 2 \left(\sum_j x_j y_j \right) r_x A_{11} A_{12} + \left(\sum_j y_j^2 \right) r_x A_{12}^2 \\ & - \left(\sum_j x_j x_j' \right) A_{11} - \left(\sum_j y_j x_j' \right) A_{12} = 0, \end{aligned} \quad (8)$$

$$\begin{aligned} & \left(\sum_j x_j^2 \right) r_y A_{12}^2 - 2 \left(\sum_j x_j y_j \right) r_y A_{11} A_{12} + \left(\sum_j y_j^2 \right) r_y A_{11}^2 \\ & - \left(\sum_j x_j' y_j \right) A_{12} + \left(\sum_j y_j y_j' \right) A_{11} = 0. \end{aligned} \quad (9)$$

The above equations are non-linear in the unknowns and were solved by a method of successive approximations. For this purpose, they were completely linearized as

$$\begin{aligned} & \left[r_x^2 \sum_j x_j^2 + r_y^2 \sum_j y_j^2 \right] \delta A_{11} + \left[(r_x^2 - r_y^2) \sum_j x_j y_j \right] \delta A_{12} \\ & + \left[2r_x A_{11} \sum_j x_j^2 + 2r_x A_{12} \sum_j x_j y_j - \sum_j x_j x_j' \right] \delta r_x \\ & + \left[2r_y A_{11} \sum_j y_j^2 - 2r_y A_{12} \sum_j x_j y_j + \sum_j y_j y_j' \right] \delta r_y = V_1, \end{aligned} \quad (10)$$

$$\begin{aligned} & \left[(r_x^2 - r_y^2) \sum_j x_j y_j \right] \delta A_{11} + \left[r_x^2 \sum_j y_j^2 + r_y^2 \sum_j x_j^2 \right] \delta A_{12} \\ & + \left[2r_x A_{11} \sum_j x_j y_j + 2r_x A_{12} \sum_j y_j^2 - \sum_j y_j x_j' \right] \delta r_x \\ & + \left[-2r_y A_{11} \sum_j x_j y_j + 2r_y A_{12} \sum_j x_j^2 - \sum_j x_j y_j' \right] \delta r_y = V_2, \end{aligned} \quad (11)$$

$$\begin{aligned} & \left[2r_x A_{11} \sum_j x_j^2 + 2r_x A_{12} \sum_j x_j y_j - \sum_j x_j x_j' \right] \delta A_{11} \\ & + \left[2r_x A_{11} \sum_j x_j y_j + 2r_x A_{12} \sum_j y_j^2 - \sum_j y_j x_j' \right] \delta A_{12} \\ & + \left[A_{11}^2 \sum_j x_j^2 + 2A_{11} A_{12} \sum_j x_j y_j + A_{12}^2 \sum_j y_j^2 \right] \delta r_x = V_3, \end{aligned} \quad (12)$$

$$\begin{aligned}
& \left[-2r_y A_{12} \sum_j x_j y_j + 2r_y A_{11} \sum_j y_j^2 + \sum_j y_j y'_j \right] \delta A_{11} \\
& + \left[2r_y A_{12} \sum_j x_j^2 - 2r_y A_{11} \sum_j x_j y_j - \sum_j x_j y'_j \right] \delta A_{12} \\
& + \left[A_{12}^2 \sum_j x_j^2 - 2A_{11} A_{12} \sum_j x_j y_j + A_{11}^2 \sum_j y_j^2 \right] \delta r_y = V_4. \quad (13)
\end{aligned}$$

In Equations (6) through (13), the prime represents the observed pixel coordinates. Unprimed represents a partial predict, the independent variable, from selenographic coordinates using the ephemeris-related transformation matrix. The quantities V_j are the negatives of the left-hand sides of Equations (6) through (9) in correspondence with Equations (10) through (13), respectively. For starting values, $r_x = r_y = 1$ was assumed together with appropriately averaged values of the coefficients determined from a least-square fit to an affine transformation. After the overall transformation was obtained by multiplying Expressions (4) and (5), producing matrix γ , the use of pixel coordinates to obtain selenographic coordinates requires a corresponding line-of-sight coordinate, z' , obtained from

$$z'^2 = R_0^2 \left(1 - \frac{x'^2}{a^2} - \frac{y'^2}{b^2} \right), \quad (14)$$

where

$$a = R_0(\gamma_{11}^2 + \gamma_{21}^2 + \gamma_{31}^2)^{-1/2} \quad (15)$$

and

$$b = R_0(\gamma_{12}^2 + \gamma_{22}^2 + \gamma_{32}^2)^{-1/2} \quad (16)$$

For the selenographic-cartesian system we, of course, have

$$z^2 = R_0^2 - x^2 - y^2 \quad (17)$$

Ten of the controls used were simply observed landmarks such as the center Langrenus, Delambre, and Tycho. In addition, from the x coordinates of the left and right limb and the y coordinates of the upper and lower limb as *observed*, center pixel coordinates were used with the computed topocentric longitude and latitude of the sub-Earth point. Also introduced as an observed quantity was the selenographic latitude, β'_R , of the right limb. From it, the selenographic coordinates of the other limb points and λ'_R could be obtained from the following formulae, which emerge from some minor spherical trigonometry.

$$\beta'_L = -\beta'_R, \quad (18)$$

$$\lambda'_L = l'_\oplus - \cos^{-1} [\tan b'_\oplus \tan \beta'_R], \quad (19)$$

$$\lambda'_R = \lambda'_L + \pi, \quad (20)$$

$$\lambda'_T = l'_\oplus + \tan^{-1} [\csc b'_\oplus \sin \beta'_R \sec b'_\oplus (1 - \sin^2 \beta'_R \sec^2 b'_\oplus)^{-1/2}], \quad (21)$$

$$\beta'_T = \cos^{-1} |\csc(l' - \lambda'_T) \sin \beta'_R \sec b'|, \quad (22)$$

$$\beta'_B = -\beta'_T, \quad (23)$$

$$\lambda_B = \lambda_T - \pi. \quad (24)$$

The four control points for the limb were given half weight in the least-square procedure because of the difficulty in being precise in evaluating β'_R , which does not correspond to a definite lunar landmark. Some limb control was considered essential, however.

In integrating the relative lunar brightness over solid angle for comparison with the lunar geometric albedo (Willey, 1976), it was necessary to make a correction for the actual condition of illumination to the condition corresponding to true geometric albedo, using the Heiligenschein region of the lunar photometric function. For this purpose, pixel coordinates individually transform to selenographic cartesian and, hence, to selenographic, by

$$\tan \lambda = x/z, \quad (25)$$

$$\sin \beta = y/R_0, \quad (26)$$

which may then be used to obtain the true phase-angle, g , through the sequence

$$\cos g_0 = \sin b_\odot \sin b'_\oplus + \cos b_\odot \cos b'_\oplus \cos(l_\odot - l'_\oplus), \quad (27)$$

$$\cos \varepsilon_0 = \sin \beta \sin b'_\oplus + \cos \beta \cos b'_\oplus \cos(\lambda - l'_\oplus), \quad (28)$$

$$\cos i = \sin \beta \sin b_\odot + \cos \beta \cos b_\odot \cos(\lambda - l_\odot), \quad (29)$$

$$\varepsilon = \varepsilon_0 + S' \sin \varepsilon_0, \quad (30)$$

$$\cos \mu = (\cos g_0 - \cos \varepsilon_0 \cos i)/(\sin \varepsilon_0 \sin i), \quad (31)$$

$$\cos g = \cos \varepsilon \cos i + \sin \varepsilon \sin i \cos \mu. \quad (32)$$

As mentioned earlier, such corrections were also required between the electrogram and each photograph on a pixel-by-pixel basis. The quantity S' is the topocentric lunar semi-diameter.

3. Discussion

It is not the main purpose of this paper to determine the new scientific conclusions to be drawn from my reduced data, especially in correlation with the many other types now available. I have instead attempted to produce a file which will be of value to the scientific community in general for many years. The complete file, as mentioned earlier, exists on magnetic tape in the form of an orthographic projection and also the standard Mercator projection of the lunar consortium. At some inconvenience, it is available in this form to the scientific community in general. Were ready accessibility to be served completely, through the printed reproduction of the file in standard catalog form, a volume of about 800 pages would result. Table 2 of the present paper represents a compromise in this regard. In it, the normal albedo and corresponding standard deviations for the intersections of the whole-degree selenographic grid curves are presented. They have been interpolated in the magnetic tape file after transfer to disk. The sampling frequency over the

selenographic grid decreases away from the mean sub-Earth point in order to remain approximately constant as a sampling frequency over the celestial sphere. The column headings are almost self-explanatory. Selenographic longitude is represented by ALAM and selenographic latitude by BET. The values are in degrees. The mean normal albedo is RHO and the standard-deviation-of-the-mean is SD. Their values are given in hundredths of a percent.

The file has been processed in a few basic ways to obtain some fundamental lunar properties. As has been cited earlier a new geometric albedo of the Moon emerges at 0.1248. At the resolution of this file, the brightest pixel is located at $\lambda = 51.4^\circ$, $\beta = -31.3^\circ$. Its normal albedo is 0.228 and it is associated with the bright crater Stevinus. Aristarchus is very slightly brighter at higher resolution, but is sufficiently smaller overall that it is fainter at the present resolution. The minimum albedo of the file at a value of 0.08956 is located in Oceanus Procellarum at $\lambda = -62.78$, $\beta = 16.57$. It is not at all conspicuous as a dark spot but is merely the minimum in a rather broad variation in brightness over the region. This is consistent with the albedo-frequency histogram of Figure 1 not possessing a foot on the dark side but only the bright side. The bright end is reasonably understood in terms of the cratering process as the source of exposure of bright surfaces which then darken with age. The more recent, hence brighter, the exposure, the fewer the impacting bodies that have produced it and the smaller the effective area. The darkening of young surfaces with cosmic exposure age emerges as rapid but continuous. Responsible for the dark side of the histogram is the completely different endogenetic process of resurfacing with basaltic rather than anorthositic material. Even if the evolution in albedo of this material is non-trivial, the observed feature in the histogram is consistent with an almost discontinuous drop in this resurfacing rate in the distant past. And if the lava flows are to be interpreted as the coalescence of many small flows of different epoch in association with a broad distribution in the size of individual flows, rather than as individual huge cataclysmic flows, then a rather weak evolutionary effect in the albedo of this material is indicated by the lack of small dark spots in the actual mapping of the file. The present study does not refute the previous reports in the literature of very small dark spots on the Moon of albedo between five and six percent, as such reports have been based on photographic materials of higher resolution, but the photometric calibration for such reports is certainly brought into question. And the incorporation of such spots into a brightness frequency histogram of corresponding spatial resolution could be expected to lead to a much sharper foot on the dark side than the bright side, a reversal of present proportions, if not even an isolated peak on the dark side. This would suggest a separate genesis for the phenomenon from what is manifest in the present histogram.

An additional immediate implication of the file is related to the general light scattering characteristics of the entire Moon. To the degree that the photometric function of the Moon is reducible to a dependence on phase angle and luminance longitude, a full Moon in the perfect sense of possessing zero phase-angle everywhere over the face (super-full Moon) should show no limb-darkening except that due to variations in the albedo associated with different lunar formations. This follows from the indeterminacy of luminance longitude at zero phase-angle. It is

easy to search the file along a series of concentric circles symmetric about the center-of-face and to compute average albedos and standard deviations. To be sure, this does not normalize-out the inhomogeneity of the lunar surface in normal albedo, but through the contributions thereof to standard deviation (or more precisely the square-root of the variance), reasonable bounds on the inferences possible are displayed. When visual observation of the full Moon suggests an absence of limb darkening one has the advantage in reaching this conclusion that he can discriminate, according to morphology, the photometric function property from the inhomogeneity in albedo. In this complex mental process, it is nevertheless difficult to place numerical bounds on the conclusion reached. In any event, the visual photometry involved is quite imprecise. In Figure 2, the black dots represent normal

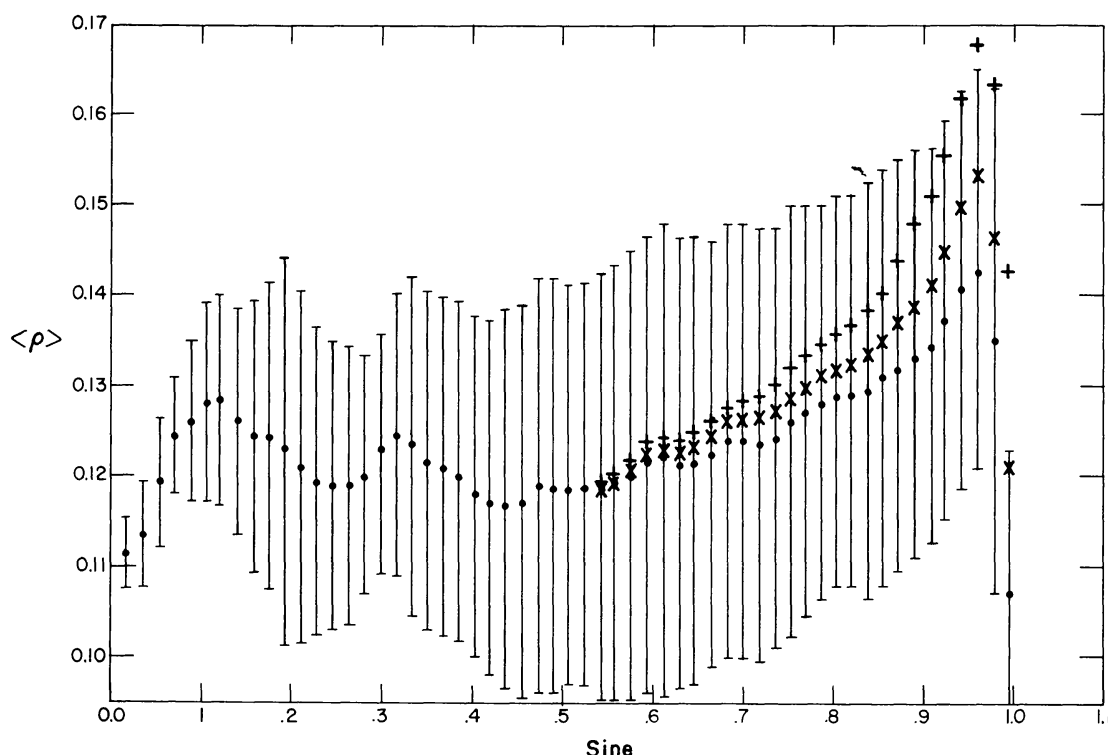


Fig. 2. The limb-darkening of the Moon obtained by averaging on circles concentric about the center of face (black dots). The brackets represent the standard-deviation for each such set of measures. The crosses and x's represent simple but unsuccessful analytical models of the limb-darkening that satisfy the reciprocity principle.

albedo averaged over loci of constant emergence angle, ε . The bars vertical to each side of the dots have lengths equal to the square root of the corresponding variance. Clearly one does not benefit from a variety in the corresponding sampling of geologic provinces at very small $\sin \varepsilon$. If we assume that a functional factor depending on ε alone multiplies the lunar photometric function in its traditional form in the neighborhood of zero phase angle, then it may be reasonably assumed that such a function is monotonic decreasing. (Such a function must actually include incidence angle except at exact zero phase angle, in order to obey the reciprocity principle, so our present inquiry is limited to exact super-full Moon.) One reason for this view is that such a function is already implicitly assumed to exist in the limiting form of one-minus-the Heaviside step-function of $(\varepsilon - (\pi/2))$ in order to

prevent the local lunar surface from being illuminated from below the local horizon. Another reason is that our Apollo Heiligenschein studies have shown values of such a function to be negligibly different from unity at moderate values of ε . In substantial harmony with this, Figure 2 shows the influence of this function does not clearly emerge until ε reaches 77° , where the factor is depressed about 8% below unity. At $\varepsilon = 84^\circ$, the depression appears close to 30%. This reading of Figure 2 should not be a spurious effect of resolution according to what we have indicated. In support of this, we note that the variance for the datum closest to the limb is *relatively* lower rather than higher in comparison to the second closest.

The functional factor accomplishing the above at small but non-zero g should be invariant to the exchange of variables i and ε . An expression of the form $(\cos \varepsilon \cos i)^k$ is one which naturally suggests itself. The x 's and the t 's in Figure 2 indicate the result of correcting albedo under such a presumption when k is set for a proper value at $\varepsilon = 77^\circ$ and 84° , respectively. Neither case appears satisfactory as the resulting curves have the same qualitative characteristics as the original curve. A more satisfactory representation can be obtained using the expression $\varphi(\varepsilon)\varphi(i)$, where we have

$$\begin{aligned}\varphi(x) &= 1 \text{ for } x < 72^\circ, \\ \varphi(x) &= [1 - 0.00625(x - 72^\circ)^2 + 0.000777(x - 72^\circ)^3 \\ &\quad - 0.0000334(x - 72^\circ)^4]^{1/2} \text{ for } x > 72^\circ, \\ \varphi(x) &= 0 \text{ for } x > 90^\circ.\end{aligned}$$

In this case the resulting functional factor is both of value 1 and has a relative maximum at $x = 72^\circ$, and it represents the data exactly at 77° , 84° , and 90° .

Further discussion of the scientific utility of the Digital Lunar Albedo File will emerge as a natural result of Lunar Consortium activities.

It is, of course, a pleasure to acknowledge the important contribution of Dr Harold Ables to the electrography utilized in this investigation. It is also a pleasure to acknowledge the fact that this investigation would never have reached conclusion were it not for the numerous rescues of the writer by Mr Eric Eliason from the insidious traps in computer systems encountered during debugging.

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ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	
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-61	-25	1587	56	-59	-25	1489	32	-57	-25	1480	26	-55	-25	1422	24	-54	-25	1504	15	-52	-25	1471	28	-50	-25	1355	37
-49	-25	1281	31	-47	-25	1282	22	-46	-25	1284	28	-44	-25	1081	17	-43	-25	1038	11	-41	-25	1049	18	-40	-25	1018	19
-39	-25	984	8	-37	-25	966	11	-36	-25	957	10	-35	-25	972	8	-34	-25	970	9	-32	-25	1010	7	-31	-25	1032	5
-30	-25	1061	13	-29	-25	1130	12	-28	-25	1203	12	-27	-25	1167	22	-25	-25	1048	13	-24	-25	1038	10	-23	-25	1104	19
-22	-25	1126	19	-21	-25	1099	13	-20	-25	1103	18	-19	-25	1067	24	-18	-25	1027	14	-17	-25	990	4	-16	-25	1008	10
-15	-25	998	12	-14	-25	1013	7	-13	-25	1011	9	-12	-25	1001	6	-11	-25	1029	25	-10	-25	1045	13	-9	-25	1051	8
-8	-25	1084	14	7	-25	1134	11	-6	-25	1177	6	-5	-25	1281	20	-4	-25	1422	23	-3	-25	1473	33	-2	-25	1466	32
-1	-25	1392	20	0	-25	1400	19	0	-25	1539	16	1	-25	1660	21	2	-25	1663	30	3	-25	1493	40	4	-25	1407	23
5	-25	1424	29	6	-25	1452	34	7	-25	1596	15	8	-25	1643	16	9	-25	1716	13	10	-25	1688	11	11	-25	1703	17
12	-25	1610	23	13	-25	1629	28	14	-25	1546	26	15	-25	1447	20	16	-25	1400	13	17	-25	1460	16	18	-25	1414	24
19	-25	1389	26	20	-25	1385	16	21	-25	1445	10	22	-25	1452	23	23	-25	1543	15	24	-25	1632	26	25	-25	1720	23
26	-25	1647	34	28	-25	1591	24	29	-25	1554	21	30	-25	1532	32	31	-25	1542	25	32	-25	1543	17	33	-25	1593	19
35	-25	1549	28	36	-25	1493	26	37	-25	1422	31	38	-25	1417	31	40	-25	1454	22	41	-25	1412	23	42	-25	1490	13
44	-25	1509	27	45	-25	1579	36	47	-25	1546	28	48	-25	1605	46	50	-25	1614	29	51	-25	1601	16	53	-25	1592	21
55	-25	1553	39	56	-25	1579	37	58	-25	1547	36	60	-25	1612	31	62	-25	1589	24	65	-25	1524	34	67	-25	1544	30
70	-25	1464	20	73	-25	1372	26	77	-25	1100	33	76	-24	1453	45	72	-24	1329	27	69	-24	1412	32	66	-24	1617	35
-64	-24	1744	49	-61	-24	1689	49	-59	-24	1484	39	-57	-24	1519	30	-55	-24	1447	29	-54	-24	1430	29	-52	-24	1414	35
-50	-24	1288	15	-49	-24	1309	12	-47	-24	1475	27	-46	-24	1356	45	-44	-24	1089	9	-43	-24	1051	12	-41	-24	1006	11
-40	-24	986	6	-39	-24	968	5	-37	-24	967	5	-36	-24	945	3	-35	-24	960	12	-34	-24	948	11	-32	-24	971	8
-31	-24	1005	6	-30	-24	1069	6	-29	-24	1116	4	-28	-24	1097	21	-27	-24	1052	9	-25	-24	1052	18	-24	-24	1127	13
-23	-24	1029	7	-22	-24	1133	14	-21	-24	1096	16	-20	-24	1082	11	-19	-24	1043	11	-18	-24	1013	7	-17	-24	1009	10
-16	-24	1049	16	-15	-24	996	10	-14	-24	990	11	-13	-24	1016	7	-12	-24	1007	7	-11	-24	1013	5	-10	-24	1038	10
-9	-24	1020	5	-8	-24	1081	13	-7	-24	1138	15	-6	-24	1176	11	-5	-24	1246	9	-4	-24	1405	22	-3	-24	1455	33
-2	-24	1378	17	-1	-24	1357	19	0	-24	1404	21	0	-24	1497	31	1	-24	1584	30	2	-24	1629	23	3	-24	1593	32
4	-24	1483	21	5	-24	1388	18	6	-24	1463	18	7	-24	1440	32	8	-24	1603	19	9	-24	1552	17	10	-24	1560	10
11	-24	1596	29	12	-24	1580	13	13	-24	1596	11	14	-24	1560	23	15	-24	1564	11	16	-24	1453	15	17	-24	1456	22
18	-24	1407	8	19	-24	1361	17	20	-24	1357	19	21	-24	1421	22	22	-24	1569	23	23	-24	1534	18	24	-24	1585	17
25	-24	1744	16	26	-24	1730	22	27	-24	1545	35	28	-24	1523	35	30	-24	1541	14	31	-24	1575	47	32	-24	1493	32

Page 10 of Table 2

ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM
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	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD
-20	-20	1185	27	-19	-20	1088	20	-18	-20	1073	13	-17	-20	1078	4	-16	-20	1051	8	-15	-20	1021	14	-14	-20	1004	12	
-13	-20	1001	10	-12	-20	1061	11	-11	-20	1039	13	-10	-20	1039	11	-9	-20	1015	13	-8	-20	1059	11	-7	-20	1135	7	
-6	-20	1245	12	-5	-20	1306	25	-4	-20	1351	16	-3	-20	1441	23	-2	-20	1394	20	-1	-20	1435	21	0	-20	1338	8	
0	-20	1313	7	1	-20	1326	10	2	-20	1397	17	3	-20	1371	21	4	-20	1362	23	5	-20	1486	25	6	-20	1419	22	
7	-20	1314	19	8	-20	1316	17	9	-20	1373	12	10	-20	1449	26	11	-20	1414	19	12	-20	1491	8	13	-20	1516	16	
14	-20	1505	16	15	-20	1490	17	16	-20	1504	15	17	-20	1493	22	18	-20	1491	15	19	-20	1488	18	20	-20	1452	16	
21	-20	1433	13	22	-20	1439	10	23	-20	1527	14	24	-20	1520	22	25	-20	1520	30	26	-20	1527	9	28	-20	1546	13	
29	-20	1601	9	30	-20	1548	24	31	-20	1427	34	32	-20	1294	19	33	-20	1247	16	35	-20	1349	16	36	-20	1358	11	
37	-20	1365	21	38	-20	1453	22	40	-20	1266	18	41	-20	1305	21	42	-20	1291	23	44	-20	1363	13	45	-20	1368	18	
47	-20	1250	9	48	-20	1262	16	50	-20	1250	25	51	-20	1236	23	53	-20	1275	17	55	-20	1299	31	56	-20	1363	33	
58	-20	1444	32	60	-20	1468	26	62	-20	1328	12	65	-20	1331	14	67	-20	1329	19	70	-20	1334	13	73	-20	1387	27	
77	-20	1131	30	76	-19	1369	26	72	-19	1291	29	69	-19	1373	46	66	-19	1418	39	64	-19	1386	33	61	-19	1394	33	
59	-19	1402	44	57	-19	1320	21	55	-19	1264	22	54	-19	1224	8	52	-19	1244	27	50	-19	1255	18	49	-19	1269	10	
-47	-19	1347	10	46	-19	1452	20	44	-19	1300	53	43	-19	1182	40	41	-19	1016	15	40	-19	1006	17	39	-19	988	19	
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ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	
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[illegible]

ALAM	BET	RHO	SD	HLAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD						
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67	-10	1334	19	70	-10	1333	12	73	-10	1362	22	77	-10	1252	39	-76	-9	1313	34	-72	-9	1330	38	-69	-9	1308	28		
66	-9	1282	23	-64	-9	1302	21	-61	-9	1303	13	-59	-9	1199	21	-57	-9	1093	17	-55	-9	1011	17	-54	-9	984	7		
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ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD
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11	32	1008	6	12	32	990	7	13	32	980	10	14	32	1016	5	15	32	1001	13	16	32	1029	14	17	32	1024	12				
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25	32	1021	11	26	32	1028	17	28	32	1199	10	29	32	1235	20	30	32	1320	26	31	32	1361	11	32	32	1287	15				
33	32	1228	9	35	32	1268	12	36	32	1328	8	37	32	1356	12	38	32	1397	16	40	32	1487	24	41	32	1510	14				
42	32	1451	36	44	32	1476	32	45	32	1521	30	47	32	1567	26	48	32	1438	22	50	32	1473	26	51	32	1493	26				
53	32	1505	16	55	32	1559	15	56	32	1531	20	58	32	1414	27	60	32	1413	20	62	32	1345	22	65	32	1421	6				
67	32	1495	28	70	32	1443	48	73	32	1122	43	77	32	928	36	76	32	959	11	72	32	933	8	69	32	964	15				
-66	33	964	11	64	33	960	11	61	33																						

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FLAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD
-24	33	972	13	-23	33	972	11	-22	33	964	9	-21	33	981	9
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3	33	1089	7	4	33	1094	8	5	33	1131	5	6	33	1150	5
10	33	1063	16	11	33	1009	9	12	33	995	8	13	33	1100	7
17	33	1043	13	18	33	1020	11	19	33	1035	8	20	33	1030	14
24	33	1070	11	25	33	1035	9	26	33	1039	14	28	33	1111	16
32	33	1233	16	33	1208	13	35	33	1281	17	36	33	1332	16	29
41	33	1437	35	42	33	1442	25	44	33	1453	23	45	33	1487	30
51	33	1457	24	53	33	1496	16	55	33	1488	31	56	33	1505	22
65	33	1456	13	67	33	1498	14	70	33	1438	10	73	33	1214	41
-69	35	943	8	-66	35	947	13	-64	35	941	9	-61	35	972	8
-54	35	971	12	-52	35	998	7	-50	35	1016	9	-49	35	1014	6
-43	35	1069	6	-41	35	1047	10	-40	35	1116	11	-39	35	1129	5
-34	35	993	15	-32	35	973	8	-31	35	1001	12	-30	35	997	8
-25	35	967	13	-24	35	955	9	-23	35	970	13	-22	35	964	14
-18	35	978	10	-17	35	968	5	-16	35	991	14	-15	35	1004	22
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-4	35	1066	9	-3	35	1086	4	-2	35	1107	8	-1	35	1133	6
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16	35	1013	13	17	35	1058	7	18	35	1052	16	19	35	1107	14
23	35	1140	7	24	35	1106	12	25	35	1061	11	26	35	1029	7
31	35	1176	6	32	35	1159	8	33	35	1155	5	35	35	1150	9
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-72	36	987	17	-69	36	958	13	-66	36	944	11	-64	36	947	8
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-19	36	984	7	-18	36	983	5	-17	36	991	9	-16	36	980	13
-12	36	1054	13	-11	36	1022	8	-10	36	1028	11	-9	36	1016	14
-5	36	1071	5	-4	36	1079	4	-3	36	1093	7	-2	36	1118	5
1	36	1108	6	2	36	1089	11	3	36	1107	11	4	36	1154	4
8	36	1301	13	9	36	1300	23	10	36	1224	22	11	36	1137	6
15	36	1017	8	16	36	1048	11	17	36	1073	8	18	36	1101	12
22	36	1205	12	23	36	1210	8	24	36	1156	9	25	36	1100	8
30	36	1187	7	31	36	1184	7	32	36	1149	9	33	36	1126	13
38	36	1256	28	40	36	1361	20	41	36	1385	26	42	36	1401	26
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-28	37	974	15	-27	37	960	11	-25	37	953	9	-24	37	961	12
-20	37	947	9	-19	37	970	11	-18	37	965	10	-17	37	978	11
-13	37	1043	11	-12	37	1055	10	-11	37	1064	13	-10	37	1032	8
-6	37	1074	11	-5	37	1092	11	-4	37	1109	8	-3	37	1146	7
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14	37	1067	8	15	37	1093	14	16	37	1117	19	17	37	1193	21
21	37	1193	12	22	37	1171	6	23	37	1154	7	24	37	1143	6
29	37	1155	14	30	37	1168	7	31	37	1152	8	32	37	1130	11

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ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD
37	37	1200	21	38	37	1325	20	40	37	1392	23	41	37	1400	13	42	37	1325	15	44	37	1339	9	45	37	1350	19				
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77	37	972	27	76	38	1009	21	72	38	987	19	69	38	961	12	66	38	934	10	64	38	943	9	61	38	960	10				
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-37	38	1117	23	36	38	1052	12	35	38	992	10	34	38	981	4	32	38	1006	12	31	38	1003	8	30	38	1000	13				
-29	38	994	17	28	38	988	14	27	38	955	16	25	38	935	6	24	38	942	6	23	38	939	6	22	38	950	11				
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-7	38	1047	14	6	38	1077	13	5	38	1088	9	4	38	1101	9	3	38	1136	15	2	38	1160	15	1	38	1177	13				
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26	40	1152	20	28	40	1172	15	29	40	1195	9	30	40	1208	17	31	40	1231	14	32	40	1234	10	33	40	1223	10				
35	40	1220	23	36	40	1266	24	37	40	1251	22	38	40	1299	19	40	40	1347	26	41	40	1382	25	42	40	1340	10				
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55	40	1434	16	56	40	1402	15	58	40	1434	17	60	40	1438	21	62	40	1461	33	65	40	1458	15	67	40	1491	17				
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-64	41	967	11	61	41	982	15	59	41	987	21	57	41	983	13	55	41	981	12	54	41	996	6	52	41	984	7				
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-23	41	968	8	22	41	962	7	21	41	946	5	20	41	963	7	19	41	959	6	18	41	971	9	17	41	987	9				
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25	41	1153	12	26	41	1189	12	28	41	1214	12	29	41	1219	18	30	41	1242	10	31	41	1264	13	32	41	1273	17				
33	41	1259	20	35	41	1244	10	36	41	1251	13	37	41	1257	19	38	41	1290	12	40	41	1393	21	41	41	1339	14				
42	41	1325	14	44	41	1396	23	45	41	1421	27	47	41	1433	30	48	41	1358	18	50	41	1304	13	51	41	1316	12				
53	41	1463	16	55	41	1510	26	56	41	1471	34	58	41	1400	20	60	41	1419	18	62	41	1431	14	65	41	1471	20				
67	41	1575	14	70	41	1529	41	73	41	1142	60	77	41	935	29	76	42	1033	24	72	42	966	8	69	42	966	12				
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ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD	ALAM	BET	RHO	SD
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-10	42	1046	10	-9	42	1044	8	-8	42	1042	10	-7	42	1041	12	-6	42	1039	6	-5	42	1071	9	-4	42	1085	9				
-3	42	1106	7	-2	42	1100	14	-1	42	1121	13	0	42	1141	11	0	42	1197	8	1	42	1245	13	2	42	1248	17				
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Page 30 of Table 2

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