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Information Theory Lateral Density Distribution for Earth Inferred from Global Gravity Field

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INFORMATION THEORY LATERAL DENSITY
DISTRIBUTION FOR EARTH INFERRED
FROM GLOBAL GRAVITY FIELD

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ABSTRACT

Information Theory Inference, better known as the Maximum Entropy Method, is used to infer the lateral density distribution inside the earth. The approach assumes that the earth consists of indistinguishable Maxwell-Boltzmann particles populating infinitesimal volume elements, and follows the standard methods of statistical mechanics (maximizing the entropy function). The GEM 10B spherical harmonic gravity field coefficients, complete to degree and order 36, are used as constraints on the lateral density distribution. The spherically symmetric part of the density distribution is assumed to be known. The lateral density variation is assumed to be small compared to the spherically symmetric part. The resulting information theory density distribution for the cases of no crust removed, 30 km of compensated crust removed, and 30 km of uncompensated crust removed all give broad density anomalies extending deep into the mantle, but with the density contrasts being the greatest towards the surface (typically ±0.004 g cm⁻³ in the first two cases and ±0.04 g cm⁻³ in the third). None of the density distributions resemble classical organized convection cells. The information theory approach may have use in choosing Standard Earth Models, but, the inclusion of seismic data into the approach appears difficult.
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INTRODUCTION

The problem addressed here is inferring via information theory the lateral density variation inside the earth from the observed external anomalous gravity field. Information theory is used because it is the least subjective way to deal with inverse problems (Baierlein, 1971). The motivation for this study is the relationship of the lateral density variation to tectonics and convection.

The nature of the problem is the following. The lateral density variation inside the earth generates the observed gravity anomalies. Hence information about the lateral density variation is provided by examining the anomalies. However, the observed gravity anomalies cannot be inverted to recover the actual density variation. The problem is nonunique: there are an infinite number of density distributions which can generate the observed gravity field. This is unfortunate, since it is desirable to know the lateral density variation, especially with regard as to how it relates to tectonics and convection (Phillips and Lambeck, 1980).

The nonuniqueness can be dealt with by various approaches in order to obtain insight into the physics of the earth. Of these modeling is by far the most common approach. Here extra assumptions are introduced until the solution to the problem becomes unique. Kaula (1963), for instance, assumes that the shear strain energy of the mantle is minimized. This key assumption, and other minor ones, together with the constraints of the observed gravity field determine a unique lateral density variation. Phillips and Lambeck (1981) review many papers which use modeling. Another approach is the Backus-Gilbert method (Backus and Gilbert, 1967, 1968; Parker, 1977), which studies all possible solutions consistent with the given data. This study is called the geophysical inverse problem (Backus and Gilbert, 1967, p. 249). The Backus-Gilbert method has been used
extensively in seismology (e.g., Jordan and Franklin, 1971). Burkhard and Jackson (1976) apply
the method to gravity data. There are also other approaches to data inversion; see, e.g., Parker
(1977), Sabatier (1977), and references contained therein.

The approach to the lateral density variation used here is that of information theory (Jaynes,
1957, 1963, 1967). This approach is commonly known as the Maximum Entropy Method, or
MEM for short. A better name would be Information Theory Inference (ITI for short), since
information theory is its basis and the name avoids confusion with thermodynamic entropy
(Baierlein, 1971, pp. 473-478). It will be called ITI here.

ITI is a probabilistic approach to nonuniqueness. Each possible answer (labelled i) to a non-
unique problem is assigned a probability $P_i$ that it is the correct answer. The probabilities $P_i$ are
assigned numerical values so as to maximize Shannon's (1948) information measure

$$MI = - \sum P_i \ln P_i$$

subject to the constraints of the known data. $MI$ in (1) stands for "Missing Information," i.e.,
the amount of information needed to determine which answer is correct (Baierlein, 1971, p. 64).
In practice the expectation value of the desired unknown quantity is taken as the inferred answer
to the problem. The information theory approach thus provides a solution to what will be called
the geophysical inference problem: picking one answer out of a number of possible answers as the
most likely to be true. ITI may hence be regarded as a complementary method to the Backus-
Gilbert method (Gull and Daniell, 1978), which investigates the geophysical inverse problem.
The rationale for using ITI is that it picks the "best" answer, dictated by the information at hand,
out of the many possible answers. "Best" here means "least subjective," i.e. the number of
unconscious assumptions in choosing an answer is minimized (Tribus and Rossi, 1973). See
Baierlein (1971, pp. 11-89) for an excellent introduction to ITI.
ITI (or MEM) has been used with great success in several different fields. One is statistical mechanics (Jaynes, 1957; Tribus, 1961; Katz, 1967; and Baierlein, 1971). In fact, (1) is the entropy function of statistical mechanics. The only difference between ITI and statistical mechanics lies in ITI's powerful information theory foundation, which allows the approach to be applied to a wide variety of problems, and not just to statistical mechanics. It has been so applied to spectral analysis (Burg, 1967, 1968, 1972) and to radio brightness maps of the sky (Gull and Daniell, 1978). In solid earth geophysics ITI has been applied to the spectral analysis of polar motion (e.g., Smylie et al., 1973; Graber, 1976), and to the radial density distribution of the earth (Rietsch, 1977; Rubincam, 1978, 1979; Graber, 1977) and of the planets (Koyama, 1979).

The present work is an extension of Rubincam (1979) to the lateral density variation. ITI is used to infer the lateral density structure based on the spherical harmonic coefficients of the gravity field and on an assumed spherically symmetric density distribution (also called the radial density distribution). The gravity field coefficients are those of GEM 10B (Lerch et al., 1981), complete to degree and order 36. The hydrostatic equilibrium bulge is subtracted out of the \( l = 2,4, m = 0 \) terms using the hydrostatic coefficients of Nakiboglu (1979). Also subtracted from the GEM 10B terms when the need arises are the gravity field coefficients of a crustal model. Two different crustal models are used: one a 30 km-thick isostatically compensated crust and the other an isostatically uncompensated crust, also 30 km thick. Carl Wagner supplied the spherical harmonic coefficients for these models (Wagner, private communication, 1976). Both sets of coefficients are complete to degree and order 36. The radial density distribution is the average structure Parametric Earth Model (PEM) of Dziewonski et al., (1975). Further, the earth is assumed to be a sphere and that the lateral density variation is small compared to the radial density distribution.

The principal results are as follows. The information theory density distribution can be written as a spherical harmonic expansion. The equation for the density variation is similar in form
to that of the equation which gives density contrasts due to lateral temperature differences.

For the cases where no crust or the 30 km thick compensated crust is removed the density contrasts are greatest near the earth's surface and have typical magnitudes of $\pm 0.004 \text{ g cm}^{-3}$. The density contrasts are also greatest near the surface for the case of 30 km of uncompensated crust removed and are typically a factor of 10 larger than in the two other cases. In all three cases the density contrasts decrease with depth but significant density anomalies still extend deep into the mantle. None of the three density distributions look like classical convection patterns, i.e., organized cells with columns of low density where material is rising and columns of high density where material is sinking. No attempt has been made in any of the cases to compute stresses or stress-differences.

**DERIVATION OF THE INFORMATION THEORY DENSITY DISTRIBUTION**

The information theory density distribution is derived from the following considerations.

It is first assumed that the data consist of the known values $F_q$ for Q integrals of the form

$$F_q = \int_V \rho(\vec{r}) f_q(\vec{r}) \, dv, \quad (q=1, 2, \ldots, Q), \quad (2)$$

where $\rho(\vec{r})$ is the earth's density distribution, $f_q(\vec{r})$ is a function which depends on position $\vec{r}$ inside the earth, $dv$ is a volume element, and $V$ is the volume of the earth. Examples of integrals of this form are the mass and moment of inertia of the earth. The gravity field coefficients also have this form, since they can be written (Phillips and Lambeck, 1980, p. 30)

$$\bar{c}_{\ell m 1} = \frac{\int_V \rho(\vec{r}) r^\ell Y_{\ell m 1}(\theta, \phi) \, dv}{(2\ell + 1) M_E a_E^6} \quad (3)$$

where $\bar{c}_{\ell m 1} = \bar{c}_{\ell m}$ and $\bar{c}_{\ell m 2} = \bar{s}_{\ell m}$ are the normalized coefficients of degree $\ell$ and order $m$, $r = |\vec{r}|$, and the $Y_{\ell m 1}(\theta, \phi)$ are surface spherical harmonics using Kaula's (1967) $4\pi$ normalization.
with $\theta$ being colatitude and $\lambda$ longitude. $M_e$ and $a_e$ are the mass and radius of the earth, respectively. Obviously in this case $F_q = C_{gml}$ and

$$f_q(\vec{r}) = \frac{r^q Y_{gml}(\theta, \lambda)}{(2q+1) M_e a_e^q}$$  \hspace{1cm} (4)

The next consideration in using ITI is to set up the earth models which constitute the various possible answers to the problem. The task is then to choose the "best" model based on the data of the form (2). The earth models are set up as follows: the earth is divided up into infinitesimal cubes, all with equal volume $dv = dx dy dz$. Each cube is labelled with the running subscript $j$.

The position vector from the center of the earth to the $j$th cube is $\vec{r}_j$. The cubes are populated with indistinguishable particles of mass $m$. Each earth model $i$ has $n_{jl}$ particles in the $j$th cube where $n_{jl}$ is an integer $\geq 0$. The density of the earth at position $\vec{r}_j$ in the $i$th model is then $\rho_i(\vec{r}_j) = n_{jl} m / dv$.

The integrals (2) for each earth model $i$ become the sums

$$F_{qi} = \sum_j \left( \frac{n_{jl} m}{dv} \right) f_q(\vec{r}_j) \, dv = m \sum_j n_{jl} f_q(\vec{r}_j).$$ \hspace{1cm} (5)

The expectation values

$$<F_q> = \sum_i P_i F_{qi}$$ \hspace{1cm} (6)

are assumed to constitute the observed values of $F_q$, where $P_i$ is the probability that the $i$th model is in fact the correct model.

The problem so formulated is analogous to the standard statistical mechanics problem of determining the population numbers of indistinguishable particles following Bose-Einstein statistics using the grand canonical ensemble (Rubincam, 1979). (Indistinguishable particles are chosen since the interchanging of particles does not affect the density distribution, which is the topic under discussion.) The solution can thus be carried out in the usual statistical mechanics fashion.
(Morse, 1969, pp. 316-319; Reif, 1965, pp. 346-349). (1) is maximized subject to the constraints of the data (6) and \( \Sigma P_i = 1 \):

\[
\frac{\partial}{\partial P_i} \left[ -\Sigma P_i \ln P_i + \alpha_0 \sum_j P_i + \alpha_1 \sum_j P_i F_{ij} + \ldots + \alpha_Q \sum_j P_i F_{Qj}\right] = 0
\]

where \( \alpha_0, \ldots, \alpha_Q \) are Lagrange multipliers, yielding \( P_i = \exp(\Sigma \alpha_q F_{qi}) / Z \), where

\[
Z = e^{1-\alpha_0} = \sum_i \exp(\Sigma \alpha_q F_{qi})
\]

is the grand partition function. Using (5) in (7) gives

\[
Z = \sum_i \exp \left[ \alpha_1 \sum_j n_{ji} f_i(\vec{r}_j) + \ldots + \alpha_Q \sum_j n_{ji} f_Q(\vec{r}_j) \right]
\]

for \( Z \), where \( \alpha_0 \) has been redefined as \( \alpha_q \). Note that the partial derivative of the logarithm of (8) with respect to \( \alpha_1 f_i(\vec{r}_j) \) gives

\[
\frac{\partial \ln Z}{\partial (\alpha_1 f_i(\vec{r}_j))} = \sum_j n_{ji} \exp \left[ \alpha_1 \sum_j n_{ji} f_i(\vec{r}_j) + \ldots + \alpha_Q \sum_j n_{ji} f_Q(\vec{r}_j) \right]
\]

\[
= \sum_j n_{ji} P_i = \langle n_j \rangle
\]

which is the expectation value of the number of particles in the cube at position \( \vec{r}_j \). This result will be used shortly.

If there are no limits to the number of particles occupying each cube, then (8) can be factored as (Morse, 1969, p. 326; Reif, 1965, p. 347)

\[
Z = \prod_j Z_j
\]
where

\[ Z_j = \sum_{n_j=0}^{\infty} \exp \left\{ \left[ \alpha_1 f_1(\vec{r}_j) + \ldots + \alpha_Q f_Q(\vec{r}_j) \right] n_j \right\} \]  

(10)

But this has the form \( \sum_{n=0}^{\infty} x^n \), which is equal to \( 1/(1-x) \). Hence (10) becomes

\[ Z_j = \frac{1}{1 - \exp \left\{ \left[ \alpha_1 f_1(\vec{r}_j) + \ldots + \alpha_Q f_Q(\vec{r}_j) \right] \right\}} \]  

(11)

Therefore

\[ <n_j> = \frac{1}{e^{\alpha_1 f_1(\vec{r}_j)} \ldots e^{\alpha_Q f_Q(\vec{r}_j)}} - 1 \]  

(12)

by (9). If it is now assumed that \(<n_j> \ll 1\), so that the Bose-Einstein statistics pass over to Maxwell-Boltzmann statistics (Reif, 1965, p. 352; Morse, 1969, p. 329), then the exponential term in the denominator of (12) is much greater than 1, and (12) simplifies to

\[ <n_j> \approx e^{\alpha_1 f_1(\vec{r}_j)} + \ldots + \alpha_Q f_Q(\vec{r}_j) \]  

Multiplying this by \( m/dv \) and dropping the subscript \( j \) gives the expression

\[ \rho(\vec{r}) = \frac{m}{dv} <n> = \frac{m}{dv} e^{\alpha_1 f_1(\vec{r})} + \ldots + \alpha_Q f_Q(\vec{r}) \]  

(13)

as the information theory density distribution. This is a most important result: it gives the form of the information theory density distribution for particles following Maxwell-Boltzmann statistics where the constraints on the density distribution have the form (2). The variance of the distribution is discussed in Appendix A.

The \( m/dv \) appearing in (13) is a troublesome factor. No commitment has been made either to the value of \( m \) or \( dv \); and there seems to be no clear guidance on how to choose their values. As it turns out, this problem may be avoided by absorbing the factor into the spherically symmetric part of the density distribution, as shown next.
The task now is to simplify (13). This involves two assumptions: first, that $f_1(\vec{r})$ pertains solely to the spherically symmetric part of the density distribution (explained below); and second, that

$$|\alpha_2 f_2(\vec{r}) + \ldots + \alpha_Q f_Q(\vec{r})| \ll 1$$

so that

$$\alpha_2 f_2(\vec{r}) + \ldots + \alpha_Q f_Q(\vec{r}) \approx 1 + \alpha_2 f_2(\vec{r}) + \ldots + \alpha_Q f_Q(\vec{r})$$

where the $f_2(\vec{r}), \ldots, f_Q(\vec{r})$ are the appropriate functions (4) for the gravity field (i.e. the anomalous density variation is small compared to the radial density.) With these two assumptions (13) becomes

$$\rho_1(\vec{r}) \approx \frac{m}{dv} e^{\alpha_1 f_1(\vec{r})} \left[ 1 + \sum_{\ell m i} \frac{\alpha_{\ell m i}}{(2\ell+1)M_E} \frac{\bar{Y}_{\ell m i}(\theta, \lambda)}{a^\ell_{\ell m i}} \right]$$

which may be written

$$\rho_1(\vec{r}) \approx \rho_o(r) + \sum_{\ell m i} \frac{\alpha_{\ell m i} \rho_o(r) r^\ell \bar{Y}_{\ell m i}(\theta, \lambda)}{(2\ell+1)M_E a^\ell_{\ell m i}}$$

(14)

where

$$\rho_o(r) = \frac{m}{dv} e^{\alpha_1 f_1(\vec{r})}$$

(15)

with $\rho_o(r)$ being the spherically symmetric part of $\rho(\vec{r})$ and where subscripts $\ell m i$ have been substituted for subscript $q$. Obviously taking $f_1(\vec{r})$ to be

$$f_1(\vec{r}) = \frac{1}{\alpha_1} \ln [\rho_o(r)dv/m]$$
results in (15). This is artificial, to be sure; no value \( f_1(r) \) in (2) is known for the earth where \( f_1(r) \) has the form given above. However, it has two advantages: the troublesome factor \( m/\delta v \) disappears, and any desired \( \rho_0(r) \) can be used in (14). The \( \rho_0(r) \) for the earth is known to a high degree of accuracy from other data: it cannot differ greatly from the PEM \( \rho_0(r) \) of Dziewonski et al., (1975). Hence it will be assumed here that the integral \( F_r \) is known for the earth where \( f_1(r) \) is given by the above equation, in order to use Dziewonski et al.'s (1975) radial density distribution.

All that remains to find the information theory density distribution is to evaluate the \( \alpha_{\text{ml}} \) using the gravity field coefficients. The raw gravity field coefficients given by (2) will not be used, however, for two reasons. The first reason is that the contribution of the earth's hydrostatic equilibrium rotational bulge to the gravity field must be subtracted out. The second reason is that the gravity field of the crust must also be subtracted from the coefficients when a crustal model is used. In this case the gravity field data become

\[
\tilde{c}_{\ell m} = \tilde{c}_{\ell m}^{\text{GEM}} - \tilde{c}_{\ell m}^{\text{CR}} - \tilde{c}_{\ell m}^{\text{HE}}
\]

for the \( \ell = \text{even}, m = 0, i = 1 \) terms and

\[
\tilde{c}_{\ell m} = \tilde{c}_{\ell m}^{\text{GEM}} - \tilde{c}_{\ell m}^{\text{CR}}
\]

for the other coefficients. The superscripts GEM, HE, and CR stand for "Goddard Earth Model," "Hydrostatic Equilibrium," and "Crust" respectively. Actually only the \( \ell = 2 \) and \( \ell = 4 \) hydrostatic equilibrium coefficients computed by Nakiboglu (1979) for Dziewonski et al.'s (1975) PEM will be used here; the higher degree hydrostatic equilibrium terms are assumed to be zero. Strictly, these terms should be included, but their computation is difficult and the error in ignoring them is probably small. All of the crustal terms up to and including degree and order 36 will, however, be subtracted from the GEM 10B coefficients when a crustal model is used.
Substituting (14) for $\rho(r)$ and $\tilde{C}_{kml}$ for $\tilde{C}_{kml}$ into (2) to evaluate $\alpha_{kml}$ yields

$$\rho_I(R) = \rho_o(R) \left[ 1 + \sum_{kml} \delta_k \tilde{C}_{kml} R^k \tilde{Y}_{kml}(\theta, \lambda) \right]$$

(16)

as the information theory density distribution, where the

$$\delta_k = \frac{(2k+1) \bar{\rho}_E}{3 \int_0^{R_U} \rho_o(R) R^{2k+2} dR}$$

(17)

are found by using the orthogonality properties of the $\tilde{Y}_{kml}(\theta, \lambda)$, where the earth is assumed to be a sphere, and where the variable $r$ has been replaced by $R = r/a$ for convenience so that $0 < R < 1$. Also, $\bar{\rho}_E$ is the average density of the earth and $a = 6371$ km is the radius of the earth.

$R_U$ is the radius of the sphere in which the unknown density distribution to be inferred resides (the subscript $u$ standing for "Upper."). For example, $R_U = 1$ if no crust is stripped off the earth and $R_U = 6341/6371$ if a 30 km thick crust is stripped off. The integral in the denominator of (17) can be evaluated analytically, since Dziewonski et al. (1975) break up the earth into eight shells, with $\rho_o(R)$ being given as a polynomial in $R$ in each shell. Table 1 gives the $\delta_k$ resulting from this computation for $R_U = 1$ and for $R_U = 6341/6371$.

RESULTS AND COMPARISONS WITH OTHER STUDIES

The fundamental equations of this paper are (16) and (17). What they give is, in a sense, the broadest possible density anomalies; more localized anomalies are not warranted by the data. Some general features of these equations should be noted before examining specific density distributions.

The information theory density distribution $\rho_I(\vec{r})$ (the subscript $I$ standing for "Information Theory") given by (16) is obviously a spherical harmonic expansion of the form

$$\rho_I(\vec{r}) = \rho_o(\vec{r}) + \Delta \rho_I = \rho_o(\vec{r}) + \sum_{kml} \tilde{\rho}_{kml}(\vec{r}) \tilde{Y}_{kml}(\theta, \lambda)$$

(18)
where

\[ \Delta \rho_1 = \sum_{\ell ml} \bar{\rho}_{\ell ml}(R) \vec{V}_{\ell ml}(\theta, \lambda), \quad \bar{\rho}_{\ell ml}(R) = \delta_\ell C_{\ell ml} R^\ell \rho_0(R). \]  

(19)

Note that \( \Delta \rho_1 \) changes discontinuously when \( \rho_0(R) \) does. Also, (16) has a form similar to that of the equation giving a density variation due to lateral temperature differences (e.g. Phillips and Lambeck, 1980, p. 32):

\[ \rho = \rho_0 \left[ 1 - \alpha(T - T_0) \right] \]  

(20)

Here \( \alpha \) is the coefficient of thermal expansion, \( \rho_0 \) and \( T_0 \) are the reference density and reference temperature, respectively, while \( T \) is the temperature. (The reason (16) has this form is due to the assumption that \( \Delta \rho_1 \) is small compared to \( \rho_0(R) \)). So (16) is consistent with the idea that the density anomalies are due to lateral temperature differences—but does not necessarily imply that the anomalies are so caused.

It should further be noted that there is no point in computing the power spectrum of the anomalous potential \( V_E^2(\Delta U) \) (e.g. Phillips and Lambeck, 1980, equation 11) generated by the density distribution (16), since the field coefficients are the given data, which (16) automatically satisfy. Moreover, the information theory density distribution (16) does not have a white noise spectrum, which Lambeck (1976) (see also Phillips and Lambeck, 1980) found will reproduce the observed anomalous potential spectrum (i.e. Kaula's (1967) rule-of-thumb). Instead the information theory density distribution \( \rho_1(R) \) concentrates the density anomalies towards the earth's surface, due to the \( R^\ell \) behavior of \( \bar{\rho}_{\ell ml}(R) \) and the \( \ell^2 \) behavior of \( \delta_\ell \) in (19). (The \( \ell^2 \) behavior may be seen by substituting \( \bar{\rho}_E \) for \( \rho_0(R) \) in (17) and evaluating the integral.) Also, it is clear from (19) that the lower degree anomalies are spread more evenly throughout the earth than the higher degree anomalies. This concentration of density anomalies towards the surface is in contrast to the findings of the Monte Carlo studies of Kaula (1977) and the mass-point studies of Lowrey (1978),
who indicate that the anomalies may increase with depth. Dziewonski et al. (1977) and Julian and Sengupta (1973), among others, also indicate that large anomalies are to be found deep within the mantle on the basis of seismic travel time studies. The statistical gravity study of Khan (1977), however, places most of the anomalies in the upper mantle. The seismic studies of Romanowicz (1979) and Cara (1979) and others show considerable upper mantle lateral structure, while the analysis of satellite-to-satellite tracking data by Marsh et al. (1981) indicates that most of the gravity anomalies in the Pacific can be explained by lithospheric sources.

It should be mentioned that the density anomalies given by (16) and (17) are not confined to the crust and mantle, but extend into the core as well. To exclude them from the core the lower limit of the integral in (17) would have to be replaced by $R_L$ (the subscript L standing for "Lower"), where $R_L = 3485.7/6371.0$, the radius of the core being 3485.7 km. In practice excluding the density anomalies from the core makes little difference in the resulting density distribution for the crust and mantle. Finally, the boundaries where $\rho_0(R)$ changes discontinuously are assumed to be spherical, so that there is no possibility of density anomalies arising from bumps on these boundaries in the manner of Hide and Horai (1968) and McQueen and Stacey (1976), for example.

The above constitute the general remarks on the information theory density distribution. Specific examples are discussed next.

A computer program was written to produce maps in order to examine specific information theory density distributions. All of the maps are based on the GEM 10B gravity field (Lerch et al., 1981). The GEM 10B field is based on satellite, surface gravity, and GEOS-3 altimetry data. Since GEM 10B is complete to degree and order 36, the limit of resolution is about 5 degrees of arc, or about 550 km on the earth's surface. All of the higher degree terms ($l \gtrsim 16$) are assumed to be meaningful, although Phillips and Lambeck (1980, p. 44) warn that these terms may largely be noise.

*See Appendix B for a listing of the program.
Plate 1 shows the density variation $\Delta \rho_i$ given by (19) overlaid on the global tectonic and volcanic activity map of Lowman (1981). The density variation is given on the surface of a sphere with radius 6368.0 km. It is at this depth, 3 km, that the oceans leave off and the rock surface begins in Dziwowski et al.’s (1975) PFM. No crust has been stripped off. The interval between contour lines is 0.002 g cm$^{-3}$. This map looks quite similar to the GEM 10B free-air gravity anomaly map (S. Klosko, private communication, 1980). It shows such typical features as the lows at Hudson Bay, Fennoscandia and some of the abyssal plains (e.g., Somali, Hatteras); and highs at some slow-moving ocean ridges (e.g., Mid-Atlantic, Southwest Indian Ocean), subduction zones (e.g., Peru-Chile, Tonga-Kermadec), and hot spots (e.g., Hawaii, Iceland). Hence for qualitatively relating density and tectonics, similar to relating gravity to tectonics as done by Kaula (1972), a free-air gravity anomaly map might just as well be used.

The map shows regions of artificial densities, due to the assumption that the earth is a sphere; the topography has been flattened. So at the Mid-Atlantic Ridge south of Iceland, for example, the effect of topography more than cancels the effect of the low density material upwelling beneath the ridge (assuming the basic validity of plate tectonics), producing a positive anomaly (Lambeck, 1972) and hence an artificially high density.

Plate 2 shows the density distribution at 30 km depth ($r = 6341$ km), where 30 km of isostatically uncompensated crust has been stripped off the earth (giving essentially the Bouguer anomalies). The interval between contour lines is 0.02 g cm$^{-3}$. Note that it gives low densities at some subduction zones. Removing the Andes, for example, completely erases the positive anomaly of Plate 1, so that low densities prevail. There is no sign of a high density subducting slab (which is probably too small to be seen in any case with the resolution employed here).

Figures 1, 2, and 3 show $\Delta \rho_i$ on a plane which slices through the center of the earth in the equatorial plane for the cases of no crust removed, 30 km of isostatically compensated crust removed, and 30 km of isostatically uncompensated crust removed, respectively. The equatorial plane was
chosen because it illustrates typical features of such slices, plus one atypical feature which appears in Figure 2.

All three figures illustrate a remark made earlier: that the information theory density anomalies extend deep into the earth, but the greatest density variation occurs near the surface. This is in qualitative agreement with Arkani-Hamed's (1970) minimum shear strain energy density distribution, but his density anomalies are much larger than those shown here. The figures also show regions where $\Delta \rho_1$ changes sign with depth. This is also in qualitative agreement with Sanchez's (1980) density distribution which minimizes the sum of the mantle shear strain energy plus gravitational potential energy. The size of the density variation shown in Figures 1 and 2 is in fair agreement with Sanchez (1980). However, the density distribution across Sanchez's (1980) slice through the equatorial plane looks nothing like those shown in the figures. It should be mentioned that the minimum energy solutions of Kaula (1963), Arkani-Hamed (1970), and Sanchez (1980) give nonhydrostatic stresses which probably exceed the finite strength of the mantle, indicating that the assumed elastic rheology is unrealistic (Lambeck, 1976, p. 6333). The alternation of the sign of $\Delta \rho_1$ with depth is also in qualitative agreement with Lewis and Dorman (1970), who used a communications theory approach to the relation of density to topography.

The information theory density distributions shown in Figures 1 to 3 clearly tend to form "pockets" of high and low density extending downwards from the surface. There is no obvious convection pattern shown in any of the figures. None of them show what look like classical convection cells; that is, organized columns of low density material moving upwards and columns of high density material moving downwards. Pockets which slant at an angle to the local normal (such as the low density region at 305 degrees east longitude shown in Figure 2, for example) look like they might indicate some sort of horizontal as well as vertical motion of material. But closer examination of the region around such features generally reveals that there are other pockets of similar density slanting towards them (as is obvious with the two low density pockets between 60
and 90 degrees east longitude shown in Figure 1, for example) which are not contoured. Hence the apparent "motion" is probably an artifact of the contouring process.

The one atypical feature mentioned earlier is the high density "blob" located at 285 degrees east longitude shown in Figure 2. Closer examination of this feature shows that it is a "tube" of high density material connecting the Peru-Chile Trench with the Middle America Trench. This feature is atypical in that the greatest density contrast occurs beneath the surface, while with the pockets the greatest density contrast occurs at the surface of the sphere inside which the density distribution is inferred.

Figures 1 and 2 are quite similar to each other. The reason for this is that the removal of a 30 km-thick isostatically compensated crust affects mostly the high degree spherical harmonic terms, and not the low degree terms considered here. The density distribution shown in Figure 3 is of course dominated by the removal of the uncompensated topography, and not the GEM 10B gravity field.

If the density anomalies of Figures 1 and 2 are assumed to be due to lateral temperature variation, then typical temperature differences of 100 K are required, assuming \( \alpha \) in (20) is about \( 3 \times 10^{-5} \) K\(^{-1}\) (e.g., Phillips and Lambeck, 1980, p. 53). The temperature differences must be about a factor of 10 greater to explain the density anomalies of Figure 3, assuming the same value for \( \alpha \).

Maps showing the density distribution with the degree of the gravity and crustal fields restricted to \( \ell \leq 16 \) also give pockets similar to those shown in the figures. Hence it appears that the qualitative behavior of the information theory density distribution will not change if terms of higher degree (\( \ell > 36 \)) than those considered here are included in the fields.
DISCUSSION

One question which arises is which of the three density distributions considered here is to be preferred. Obviously the one in which no crust is removed is over-abstracted: no account is taken of the topography. So it is not the preferred density distribution. The density distribution in which 30 km of uncompensated crust is removed has intriguing consequences for the deep structure of continents (e.g., Jordan, 1975; but see Anderson, 1979): very deep indeed. However, the geophysical evidence favors the density distribution in which 30 km of compensated crust is removed; so it is preferred. But it is not ideal: it assumes that the topography is isostatically supported everywhere over the earth; and, moreover, with a depth of compensation of 30 km. This is certainly not the case. To cite just one example where the assumptions fail, no account is taken of thermal isostacy at the ocean ridges (Haxby and Turcotte, 1978), where the effective depth of compensation is greater than 30 km. Hence the density distribution still gives a high density for the Mid-Atlantic Ridge south of Iceland, for example, after the crust is removed, when it should be low density. Hence better models of the crust are needed in order to use ITI to infer the density distribution below it.

Another question which arises is why the information theory density distribution disagrees with the results of Lambeck (1976), Kaula (1977), and Lowrey (1978) which are also based solely on the relationship of density to gravity (and not on seismic travel times), and which give large density anomalies in the lower mantle. The answer appears to be that these studies examine only a limited number of models which mimic the external gravity field, while the information theory density distribution is a weighted average over all possible density models and reproduces the external gravity field exactly.

The reason why the information theory density distribution disagrees with the seismic evidence of Julian and Sengupta (1973), Dziewonski et al. (1977) and others, which also give large anomalies in the lower mantle, seems clear enough: the seismic data have not been included in the information theory approach. Their inclusion presumably would show large anomalies in the lower mantle.
The dominant impression from the foregoing remarks on the problem addressed here is one of simplicity. More data must be introduced to obtain results which are closer to the actual state of affairs inside the earth. Taking the earth to be made up of indistinguishable particles following Maxwell-Boltzmann statistics is an obviously simplifying, if fundamental assumption which must also be dealt with in order to obtain more realistic results.

Introducing seismic travel times into the approach appears to be an obvious next step to take in examining the density anomalies. However, including the seismic travel time data into ITI appears to be difficult. It is not obvious how to put such information into an approach which sums over all possible models. Numerical models are out of the question: dividing up the earth into 10 volume elements each of which may be occupied by up to 10 particles gives $10^{10}$ models to consider — far too many already for a computer. Thus the problem must be done analytically. But even such a seemingly simple task as using free oscillation periods to obtain a spherically symmetric earth model has analytical difficulties: the data do not have the simple form (2), and the elastic parameters vary as well as the density. These difficulties make the evaluation of the partition function $Z$ troublesome (Graber, 1977). The variance (see Appendix A) and choosing $m/dv$ in (13) also post difficulties in applying ITI.

On the positive side is the heart of the method: ITI (MEM) minimizes subjectivity. To illustrate, there is no need in ITI to decide which lower degree harmonics to ignore in examining density anomalies in the lithosphere (e.g., Marsh et al., 1981), which is a highly subjective procedure. ITI weights all the harmonics automatically. And since ITI gives the one "best" (i.e., least subjective) model, it may well have use in choosing a Standard Earth Model, although the mathematical obstacles mentioned earlier would have to be overcome.
ACKNOWLEDGMENTS

I wish to thank David E. Smith for many helpful discussions and other valuable assistance. Discussions with Mike Graber were also very useful. Carl Wagner supplied the crustal models and the rock-equivalent topography. I thank Barbara Putney and Tom Odt for programming help. The support of the Director's Discretionary Fund of the Goddard Space Flight Center is gratefully acknowledged. The Technical Memorandum of Rubincam (1979) was erroneously numbered 80549. It should be 80586.
REFERENCES


McQueen, H. W. S., and F. D. Stacey, Interpretation of low degree components of gravitational potential in terms of undulations of mantle phase boundaries, *Tectonophysics*, 34, T1-T8, 1976.


Plate 1. Lateral density variation $\Delta \rho$, at 3 km depth (no crust removed). Note that no zero line is shown, which would make the map too busy.
Plate 2. Lateral density variation in $\Delta \rho$, at 30 km depth for 30 km of uncompensated crust removed.

Note that no zero line is shown, which would make the map too busy.
Figure 1. Lateral density variation $\Delta \rho_1$ in the equatorial plane of the earth for the case of no crust removed. Sea level is displaced from the earth's surface for clarity, and the rock-equivalent topography is greatly exaggerated. Anomalies in the core are not shown.
Figure 2. Lateral density variation $\Delta \rho_1$ in the equatorial plane of the earth for the case of 30 km of compensated crust removed. Sea level is displaced from the earth’s surface for clarity, and the rock-equivalent topography is greatly exaggerated. Anomalies in the core are not shown.
Figure 3. Lateral density variation $\Delta \rho_1$ in the equatorial plane of the earth for the case of 30 km of uncompensated crust removed. Sea level is displaced from the earth's surface for clarity, and the rock-equivalent topography is greatly exaggerated. Anomalies in the core are not shown.
FIGURE CAPTIONS

Plate 1. Lateral density variation $\Delta \rho_i$ at 3 km depth (no crust removed). Note that no zero line is shown, which would make the map too busy.

Plate 2. Lateral density variation $\Delta \rho_i$ at 30 km depth for 30 km of uncompensated crust removed. Note that no zero line is shown, which would make the map too busy.

Figure 1. Lateral density variation $\Delta \rho_i$ in the equatorial plane of the earth for the case of no crust removed. Sea level is displaced from the earth's surface for clarity, and the rock-equivalent topography is greatly exaggerated. Anomalies in the core are not shown.

Figure 2. Lateral density variation $\Delta \rho_i$ in the equatorial plane of the earth for the case of 30 km of compensated crust removed. Sea level is displaced from the earth's surface for clarity, and the rock-equivalent topography is greatly exaggerated. Anomalies in the core are not shown.

Figure 3. Lateral density variation $\Delta \rho_i$ in the equatorial plane of the earth for the case of 30 km of uncompensated crust removed. Sea level is displaced from the earth's surface for clarity, and the rock-equivalent topography is greatly exaggerated. Anomalies in the core are not shown.
Table 1

The Coefficients $\delta_\xi$ for No Crust Removed ($R_u = 1$) and 30 km of Crust Removed ($R_u = 6341/6371$).

<table>
<thead>
<tr>
<th>Degree $\xi$</th>
<th>$\delta_\xi$</th>
<th>$R_u = 1$</th>
<th>$R_u = 6341/6371$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.096</td>
<td>1.112</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2.794</td>
<td>2.857</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>5.285</td>
<td>5.445</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>8.580</td>
<td>8.911</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>12.701</td>
<td>13.295</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>17.659</td>
<td>18.635</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>23.467</td>
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</tr>
<tr>
<td>8</td>
<td>30.130</td>
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<td>37.653</td>
<td>40.715</td>
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<td>55.283</td>
<td>60.771</td>
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<td>12</td>
<td>65.392</td>
<td>72.479</td>
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<td>36</td>
<td>571.458</td>
<td>771.647</td>
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</table>
APPENDIX

Finding the variance \( \sigma_n^2 = \langle n_j^2 \rangle - \langle n_j \rangle^2 \) from (8) closely follows the standard statistical mechanics treatment (e.g., Reif, 1965, pp. 336-337). It is given by

\[
\sigma_n^2 = \frac{\partial^2 \ln Z}{\partial \left( \alpha_i \Gamma_i \langle n_j \rangle \right)^2}
\]

which gives

\[
\frac{\sigma_n}{\langle n_j \rangle} = \sqrt{1 + \frac{1}{\langle n_j \rangle}} = \frac{\sigma_\rho}{\rho(r)}, \quad \sigma_\rho = \frac{m}{dV} \sigma_n
\]

for particles following Bose-Einstein statistics (Reif, 1965, p. 346; Morse, 1969, p. 333). Because it is assumed that \( \langle n_j \rangle \ll 1 \), all that can be said about \( \sigma_\rho \) is that \( \sigma_\rho > \rho(r) \), since no commitment to the value of \( \langle n_j \rangle \) has been made. Hence the data do not greatly constrain the density distribution.
The computer program used to generate the plates and figures is listed here. Plates 1 and 2 use subroutine VANDER. Figures 1, 2, and 3 use subroutine SLICE.

*INFORMATION THEORY DENSITY DISTRIBUTION*

THIS PROGRAM COMPUTES THE INFORMATION THEORY DENSITY DISTRIBUTION. IT ASSUMES MAXWELL-BOLTZMANN STATISTICS AND THAT THE SPHERICALLY SYMMETRIC PART OF THE DENSITY DISTRIBUTION IS KNOWN.

THE PROGRAM USES SPHERICAL HARMONICS. THE LATERAL DENSITY VARIATION IS ASSUMED TO BE A SMALL PERTURBATION ON TOP OF THE SPHERICALLY SYMMETRIC DENSITY DISTRIBUTION.

THE PROGRAM COMPUTES THE DENSITY VARIATION, RELATIVE DENSITY, OR ACTUAL DENSITY INSIDE THE EARTH, WHICH MAY BE DISPLAYED IN VARIOUS WAYS ACCORDING TO A CHOSEN SUBROUTINE. THE DISPLAY IS IN ONE OF TWO MODES: PRINT-OUT PICTURES OR DECODING PHOTOGRAPHS.

THE CENSITY IS DEFINED AS THE SPHERICALLY SYMMETRIC PART (RHO-SUB-ZERO) PLUS THE DENSITY VARIATION (DELTA RHO). THE RELATIVE CENSITY IS DEFINED AS DELTA RHO DIVIDED BY RHO-SUB-ZERO.

CRUSTAL MODELS (SUCH AS AN ISOSTATICALLY COMPENSATED CRUST) OR AN ISOSTATICALLY UNCOMPENSATED CRUST) MAY BE SUBTRACTED OFF IF DESIRED AND THE INFORMATION THEORY ALGORITHM APPLIED TO THE REMAINING GRAVITY SIGNAL.

ALSO, THE DEGREES USED BY THE SPHERICAL HARMONIC FIELDS CAN BE RESTRICTED TO A CERTAIN RANGE (BETWEEN LMIN AND LMAX INCLUSIVE) IF DESIRED.

\[ a \] NOTATION

GENERAL DATA

PI = 3.1415926535897900
PIDIV = PI/2.000
PI2 = 2.000*PI
LLOW = MINIMUM DEGREE OF GRAVITY/TOPOGRAPHY/CRUSTAL FIELD RECORDS READ
LUP = MAXIMUM DEGREE OF GRAVITY/TOPOGRAPHY/CRUSTAL FIELD RECORDS READ
LPIH = MINIMUM DEGREE OF GRAVITY/TOPOGRAPHY/CRUSTAL FIELD TO BE USED IN PROGRAM
LPHI = MAXIMUM DEGREE OF GRAVITY/TOPOGRAPHY/CRUSTAL FIELD TO BE USED IN PROGRAM
SUBNAME = NAME OF SUBROUTINE CALLED
COMMENT = GENERAL COMMENTS ABOUT PARTICULAR RUN (SUCH AS THE NAME OF THE REGION BEING EXAMINED, ETC)
NPRINT = 1 IF GRAVITY/TOPOGRAPHY/CRUSTAL FIELD COEFFICIENTS ARE TO BE LISTED, 0 IF NOT

EARTH DATA

RHOAVG = AVERAGE DENSITY OF THE EARTH IN GRAMS/CM**3
RADOV = AVERAGE RADIUS OF EARTH IN KILOMETERS
RCORE = RADIUS OF OUTER CORE IN KILOMETERS
RLOWER = LOWER LIMIT ALLOWED FOR DENSITY ANOMALIES, IN KILOMETERS
RUPPER = UPPER LIMIT ALLOWED FOR DENSITY ANOMALIES, IN KILOMETERS
RMID = UPPER/LOWER LIMIT ALLOWED FOR DENSITY ANOMALIES, IN KILOMETERS

GRAVITY FIELD

GREAT = DESCRIPTION OF GRAVITY FIELD
CRUST = DESCRIPTION OF CRUSTAL MODEL
MCORE = DESCRIPTION OF CORE MODEL FIELD IS SUBTRACTED FROM GRAVITY FIELD, 0 IF NOT

TOPOGRAPHY

TTOP = DESCRIPTION OF TOPOGRAPHY
TOPO = ARRAY IN WHICH TOPOGRAPHY COEFFICIENTS ARE STORED

LATERAL DENSITY DISTRIBUTION

COORD = REMARKS ABOUT THE COEIL (SUCH AS THE DEPTHS FOR WHICH

33
THEY WERE WOWED)
ONCE - INFORMATIVE THEORETIC COEFFICIENTS BASED ON THE
SPHERICALLY SYMMETRIC DENSITY DISTRIBUTION.
PLOTTED, +1 IF
ACTUAL DENSITY IS PLOTTED, +2 IF DENSITY VARIATION IS
PLOTTED.
REFERENCE DENSITY, USED ONLY IF NOEN=1.

PICTURE DATA

SAMPLE INPUT DATA (COLUMN 1 OF INPUT STARTS IN COLUMN 3 HERE)

LLON LUP (FORMAT: 4F5.1)
36 36

LMIN LMAX (FORMAT: 4F5.1)
36 36

ACCRST APRINT (FORMAT: 4F5.1)
1 1

C RADAVG RCOORD RANG (FORMAT: 8F10.5)
671.6 3495.7 5.517

C DENSY COEFFICIENTS (COEFF.) (RANGE: 670 TO 30 KM DEPTH)

C RLOAD RUPAX (FORMAT: 8F10.5)
5701.0 6341.0

K COE (FORM: 8F10.5)
1 33.5930062
2 3.4100380
3 723.46557
36 771.49419

(COAV[J], J=1,1A) (FORMAT: 13E6.2)
ORIGINAL PAGE IS OF POOR QUALITY
FIND THE RELATIVE DENSITY, DENSITY, OR DENSITY VARIATION ON EACH CUT.

COMPUTE THE RELATIVE DENSITY, DENSITY, OR DENSITY VARIATION AT POINT/CUT.

THIS SUBROUTINE COMPUTES THE RELATIVE DENSITY, DENSITY, OR DENSITY VARIATION ON VERTICAL RECTANGLES (CUTS) WHICH ARE PERPENDICULAR TO A GREAT CIRCLE CONNECTING TWO POINTS ON THE EARTH'S SURFACE AT INTERVALS EQUALLY SPACED ALONG THE GREAT CIRCLE SEGMENT.

FIND THE RELATIVE DENSITY, DENSITY, OR DENSITY VARIATION ON EACH CUT.

COMPUTE THE RELATIVE DENSITY, DENSITY, OR DENSITY VARIATION AT POINT/CUT.

THE LACINGS OF A FOOTBALL (WITH THE CUTS EXTENDING VERTICALLY)

THE CUTS ARE DISPLAYED AS RECTANGLES, SO THAT THERE IS A CERTAIN AMOUNT OF DISCONTINUITY. ONE IS LOOKING AT THE Cuts IN THE FOLLOWING WAY:

- The two points connected by the great circle segment may be chosen at will. The number of cuts, their length, and their depth may also be chosen at will. There is always a cut at each endpoint of the great circle segment.

- The two points connected by the great circle segment may be chosen at will. The number of cuts, their length, and their depth may also be chosen at will. There is always a cut at each endpoint of the great circle segment.

NOTATION:

PHI1 = LATITUDE OF FIRST GREAT CIRCLE ENDPOINT IN DEGREES

XLMCA1 = LONGITUDE OF FIRST GREAT CIRCLE ENDPOINT IN DEGREES

PHI2 = LATITUDE OF SECOND GREAT CIRCLE ENDPOINT IN DEGREES

XLMCA2 = LONGITUDE OF SECOND GREAT CIRCLE ENDPOINT IN DEGREES

DEPT1 = DEPTH TO LOWER CUT BOUNDARY IN KILOMETERS

DEPT2 = DEPTH TO UPPER CUT BOUNDARY IN KILOMETERS

ARCLNG = LENGTH OF CUT IN DEGREES

TCLERE = TOLERANCE LIMIT IN DEGREES, BELOW WHICH A SMALL DIFFERENCE IN LATITUDE OR LONGITUDE OF THE GREAT CIRCLE ENDPOINTS IS SET EQUAL TO ZERO TO AVOID SINGULARITIES

NCUT = NUMBER OF CUTS ALONG THE GREAT CIRCLE SEGMENT

NHORZ = LENGTH OF CUT IN SPACES ACROSS PAGE FOR PHOTO

XPACNI = MAGNIFICATION OF DEPTH COMPARED TO LENGTH OF CUT (+1.0 FOR TRUE DEPTH TO LENGTH RATIO)

SUBROUTINES CALLED:

1. ANGLE
2. DENSITY
3. SPACE
4. VEC

NOTES:

1. XLMCA1 <= XLMCA2.
2. DEPT1 > DEPT2.
3. NHORZ IS ODD AND <= 121.
4. DEPT1 IS USUALLY CHANGED SLIGHTLY BY THE SUBROUTINE TO MAKE THE VERTICAL LENGTH OF THE Cuts AN INTEGER NUMBER OF SPACES LONG ON THE PRINT-OUT PICTURE (OR DANCED PHOTOCOPY).
5. NCUT > GT1.

SAMPLE INPUT DATA (COLUMN 1 OF INPUT STARTS IN COLUMN 3 HERE)

SUBNAME

CUTS

ICOMPENT(J3, J2+1, 1, 1)

FRENCH

PHI1, XLMCA1, PHI2, XLMCA2, DEPT1, DEPT2 (FORMAT=4F6.0)
the spherical rectangles are displayed as rectangles with the east-west direction running horizontally across the page (photograph). so there is a certain amount of distortion.

rotation

r1 = radial distance of lowest rectangle in kilometers
r2 = radial distance of highest rectangle in kilometers
theta1 = colatitude of northern boundary of the rectangles in degrees
theta2 = colatitude of southern boundary of the rectangles in degrees
xlamda1 = longitude of the western boundary of the rectangles in degrees
xlamda2 = longitude of the eastern boundary of the rectangles in degrees
nspace = length of the northern and southern boundaries in horizontal spaces across the page (photograph).
nsurf = number of rectangles desired

subroutines called:

1. censky

notes

1. r2 < r1.
2. theta2 < theta1.
3. xlamda2 < xlamda1.
4. nspace < nsurf.
5. nsurf < r1.

sample input data (column 1 of input starts in column 3 here)

* summary
(format: a6)
(piece)
(ncopy(2), j=1,14)
(format: 13f, a2)

* parameters

r1 r2 theta1 theta2 xlamda1 xlamda2 nspace nsurf

* input data

* implicit real* alpha(10,0:2)
integer* xlamda(121), beta(111)
dimension alpha(212), lcmf(205,21)
dimension xlamda(121)
dimension copyt(112)
copy/ pylk, spmp

write (160300, i, format) (i, j=1,14)
write (160310, i) format (10x, 13a4, a2, //)

find pixels of sympl/CCCR range

sum=A+sumyp

sum=strep+2.00c + C.500

if (aphetilo .eq. 0.0) strep=1.000

write (6,11) format (11i1)
write (6,12) format (3f, i)
write (6,13) format (11i1)
write (6,14) format (11i1)
write (6,15) format (11i1)
write (6,16) format (11i1)
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write (6,21) format (11i1)
write (6,22) format (11i1)
write (6,23) format (11i1)
write (6,24) format (11i1)
write (6,25) format (11i1)
write (6,26) format (11i1)
write (6,27) format (11i1)
write (6,28) format (11i1)
write (6,29) format (11i1)
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write (6,31) format (11i1)
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write (6,71) format (11i1)
write (6,72) format (11i1)
write (6,73) format (11i1)
write (6,74) format (11i1)
C CCNPAP ANGLES FROM DEGREES TO RADIANS
C THEATA, THEETA, THEETA1, THEET2
C THEETA + THEETA1 = THEETA2
C KLMCA + KLMDA = KLMCA2
C WRITE (6,1) THETA, THEETA, THEETA1, THEET2
C WRITE (6,1) KLMCA, KLMDA, KLMCA2
C WRITE (6,11) XLMCA, XLMCA2, XLMCA3
C WRITE (6,12) XPAP(KI,1,122)
C allocate
C CC INITIALIZE LINE VALUES
C XPAP IS FOR PRINT-DIPT PICTURE
C XPAP IS FOR DISCRIPT PHOTO
C XPAP(KI,1,122)
C K = N2* DR
C DC 1 (SURF1,1,INSURF)
C HHH = DR
C THEETA + THEETA1 = THEETA
C DC 1 (THEETA,1,111)
C THEETA + THEETA1 = THEETA2
C KLMCA + KLMDA = KLMCA2
C XPAP(KI,1,122)
C allocate
C CC CONTINUE
C PRINT THE LINE
C WRITE (6,14) XPAP(KI,1,122)
C WRITE (6,15) XPAP(KI,1,122)
C XPAP(KI,1,122)
C XPAP(KI,1,122)
C allocate
C CC SUBCUTING PCLES (RMM, RMMAX, RMM, NPOLE)
C allocate
C CC...
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SUBROUTINES CALLED
1. ANGLE
2. CIRC
3. CENT

NOTES
1. ANCMAX > 90 DEGREES.
2. NRAD > 90.

SAMPLE INPUT DATA (COLUMN 1 OF INPUT STARTS IN COLUMN 3 HERE)

NAME

(IMPRTNTJ, J=1,14) (FORMAT: 1346,42) PCL 24

SURFACE CENSITY DISTRIBUTION

NRAD ANCMAX NRAD (FORMAT: 15,3F10.5) PCL 26

34 50.0 637.0 C

IPPLICIT REAL*8(1=10,J=2)

IWRITE 

WRITE 16.161

WRITE 16.302 NRAD

WRIT EX 1693031 ANGPA

R-RKM/PAOAVO PCL 27

ANGM-ANGMAX*F

SANG

C

FINIE MIDCLE OF SYMECL/CECLR RANCE

SYMMAXSYMMAX+2.60C + C.100

COMPUTE NUMBER OF HORIZONTAL LINES IN MAP

NROSEC=NRAD

NRAD=NRAD

NRY=NRDSEC/5

NRY=NRY+NRY

NRY=NRY+NRY

**NRY

CC . - VG LEFT AND RIGHT LIMITS OF MAP BY CALLING CIRC

CALL CIRCNRSEC

DC 1C NUPMAP=1,1

C INITIALIZE LINE VALUES

XMAP IS FOR PRINT=CLT PICTURE

TMAP IS FOR DISCRETE PICTUR

DC = 14,121

TMAPX = TMAP2

V

WRITE 16.161

XFCRPA (INI) IF (FPOLE =C.G.1) WRITE (6,301) PCL 81
IF INPOLE .EQ. 2 WRITE (6,21)
  20 FORMAT (20X,NORTH,3E14.12)
PCL 82
  30 FORMAT (20X,SOUTH,3E14.12)
PCL 83
  40 C FINE THE RELATIVE DENSITY, DENSITY, OR DENSITY VARIATION ON EACH PCL 84
  50 CALL HORIZONTAL LINE
  60 DO 2 LPL+1
  70 LPL+1 = LPL+1
  80 KPL+1 =LON(H,L)
  90 KPA+LON(H,L,2)
 PCL 86
 100 DC 3 =X,NH,R
 PCL 87
 110 C FINE THE y,y2, COORDINATES OF EACH POINT ON THE LINE PCL 88
 120 F(LY) = 60.000
 PCL 89
 130 SY =SY +.002/4.000
 PCL 90
 140 SYSY +SY SY/4.000
 PCL 91
 150 CALL THE SPHERICAL POLAR COORDINATES OF POINT PCL 92
 160 CALL ANGLERY,Y,ALPHA)
 PCL 93
 170 IF INPOLE .EQ. 2 ALPHA =-12 =ALPHA
 PCL 94
 180 XPAP=CSINTY +Y=2)
 PCL 95
 190 SINH =SY=SY=SANG=SANG=SINTH
 PCL 96
 200 IF SY =-1.000 220,201 PCL 97
 210 WRITE (6,203) NRAC,RCES,NX,NY,NX1,LP,LY,K PCL 98
 220 FCPPAT =154,1159 PCL 99
 230 WRITE (6,204) RCES,RF2,LY,FLY,RF2,RF3,RF4 PCL 100
 240 CALL FCPPAT =154,1159 PCL 101
 250 CALL HORIZONTAL LINE
 PCL 102
 260 IC IC IC
 PCL 103
 270 CALL CONTINUE
 PCL 104
 280 CONTINUE
 PCL 105
 290 CALL CONTINUE
 PCL 106
 300 CALL CONTINUE
 PCL 107
 310 CALL CONTINUE
 PCL 108
 320 CALL CONTINUE
 PCL 109
 330 CALL CONTINUE
 PCL 110
 340 CALL CONTINUE
 PCL 111
 350 CALL CONTINUE
 PCL 112
 360 CALL CONTINUE
 PCL 113
 370 CALL CONTINUE
 PCL 114
 380 CALL CONTINUE
 PCL 115
 390 CALL CONTINUE
 PCL 116
 400 CALL CONTINUE
 PCL 117
 410 CALL CONTINUE
 PCL 118
 420 CALL CONTINUE
 PCL 119
 430 CALL CONTINUE
 PCL 120
 440 CALL CONTINUE
 PCL 121
 450 CALL CONTINUE
 PCL 122
 460 CALL CONTINUE
 PCL 123
 470 CALL CONTINUE
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 480 CALL CONTINUE
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 490 CALL CONTINUE
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 500 CALL CONTINUE
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 510 CALL CONTINUE
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 520 CALL CONTINUE
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 530 CALL CONTINUE
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 540 CALL CONTINUE
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 550 CALL CONTINUE
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 560 CALL CONTINUE
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 570 CALL CONTINUE
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 590 CALL CONTINUE
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 770 CALL CONTINUE
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 780 CALL CONTINUE
 PCL 155
 790 CALL CONTINUE
 PCL 156
 800 CALL CONTINUE
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 810 CALL CONTINUE
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 820 CALL CONTINUE
 PCL 159
 830 CALL CONTINUE
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 840 CALL CONTINUE
 PCL 161
 850 CALL CONTINUE
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 860 CALL CONTINUE
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 870 CALL CONTINUE
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 880 CALL CONTINUE
 PCL 165
 890 CALL CONTINUE
 PCL 166
 900 CALL CONTINUE
 PCL 167
 910 CALL CONTINUE
 PCL 168
 920 CALL CONTINUE
 PCL 169
 930 CALL CONTINUE
 PCL 170
 940 CALL CONTINUE
 PCL 171
2. CIRC
3. CENSYS

SAMPLE INPUT DATA (ICLMMN 1 OF INPUT STANTS IN COLMMN 2 HERE)

C SUBRMS
C SECTIONS
C MPEX IJ)

C CIRC enthus (FMTA)
C MPEX (FMTA)

C PRINT INPUT DATA
WRITE (6,1016)
WRITE (16,300)
WRITE (6,1021)
WRITE (6,1030)
WRITE (6,1040)
WRITE (6,16)  
FCMPAT (100)  
NSPACE = 128 - ANY  
DC 17 KX=1, NSPACE  
WRITE (6,18) ALPHAI(133)  
FFNAT (10X,1A1)  
14  
RD = F*JXJXPIXPER/PERI  
C FIND THE RELATIVE DENSITY, DENSITY, OR DENSITY VARIATION ON EACH LINE SEC 94  
C HORIZONTAL LINE SEC 97  
C FIND THE X, Y, Z COORDINATES OF EACH POINT ON THE LINE SEC 93  
Z = IXI + PERI  
STERC = 100.000 - 0.007  
IF (PERI .GE. 100) SEC 100  
Y = (FLI - RTI) * (STERC/PERI)/RADS  
RPA = LONHLI(LP1)  
DC 3 X = RMIN(RPAX)  
FX = 1  
X = (FX - 61.000) * (ERUP/ARADSEC)  
C FIND THE SPHERICAL POLAR COORDINATES OF POINT SEC 110  
G = THE POINT IN THE CIRCLE SEC 112  
IF (FR .LE. RCORE) 20  
20 CONTINUE SEC 118  
21  
R IS USED FOR GKE SEC 119  
OC IC 29  
22  
C IS THE POINT BELOW THE EARTH SEC 118  
IF (EK .LE. MLONEX) 101  
101 DENS = 0.00  
OC IC 103  
102 CONTINUE SEC 122  
23  
XSCP = COS(R * ZOUT) * (ZOUT + 1) * (ZOUT - 1)  
IF (Z .LE. 24.25.20) SEC 126  
24  
T = ETA + PI/2  
OC IC 26  
25  
XSCV = COS(T)  
OC IC 24  
26  
T = ETA + PI/2  
OC IC 22  
27 CONTINUE SEC 131  
28  
CALL ANGLG(X,Y,XLPO/) SEC 136  
C COMPUTE THE RELATIVE DENSITY, DENSITY, OR DENSITY VARIATION AT POINT SEC 133  
C GKE = THE CIRCLE (1,THETA,KLMAP,ONEN,REFDEN,DEN) SEC 134  
C CONTINUE SEC 135  
C PUT THE RIGHT SYMBOL/NUMBER IN XMAP(K)/IMAP(K) SEC 136  
K = (CEN SCALE) + 0.5D  
JAUP = SYML * X  
IF (JAUP .GE. 11.111) SEC 138  
IF (JAUP < JMAX) SEC 140  
29  
XMAP(K) = ALPHAI(JNUP)  
JAUP = JMAX  
IF (JAUP < JMAX) SEC 141  
3  
CONTINUE SEC 143  
C PRINT THE LINE SEC 144  
WRITE (6,14) (XMAP(I), I = 1,121)  
14  
FCMAT (150,121)  
WRITE (6,100) (IMAP(I), I = 1,121)  
100  
FCMAT (121,121)  
C RESET THE LINE SEC 149  
DC 15 XMAP(K)/MAX  
XPAP(K) = ALPHAI(23)  
FPAPI(K) = RETAIL  
15  
CONTINUE SEC 153  
2  
CONTINUE SEC 154  
KLM = PHI (180.000/FI)  
C PRINT LATITUDE OF EACH SECTION SEC 156  
WRITE (6,30) KLM  
30  
FCMAT (150,400,*LATITUDE+1,FIN.+DEGREET) SEC 158  
C CONTINUE SEC 159  
RETURN SEC 160  
END SEC 161  
1  
SUBCUTINE SLICE (PHI1,KLMDA1,PHI2,KLMDA2,TOLER,ARAD)  
S1  
CO
CO
#SLICE*  
S1 2  
CO
CO
THIS SUBROUTINE COMPARES THE RELATIVE DENSITY/DENSITY/DENSITY VARIATION ON A PLANE WHICH Passes Through The CENTER OF THE EARTH.  
S1 3  
THE INTERSECTION OF THE PLANE WITH THE EARTH IS CALLED A SLICE.  
S1 4  
THE SLICE IS ORIENTED SC AS TO CONTAIN THE TWO POINTS  
S1 6  
C (PHI1,KLMDA1) AND (PHI2,KLMDA2), THE LINE WHICH FORMS THE  
S1 7
SINC 0.000
CC IC A1
80
TCCLP=CD(SLINPDA2*XLBNPDA2)
SLI 78
C IS THE GREAT CIRCLE A MERC IDIAN?
SLI 79
IF (TCCLP = TCCLP) 82, 13, 83
SLI 80
82
XNP=PICICV
SLI 81
CSSNP=CSSNP+CSSNP
SLI 82
SINNP=SINNP
SLI 83
OPEACHL(EICPECA)
SLI 84
SINCIC=SINCIC
SLI 85
GC IC A1
SLI 86
83
CONTINUE
SLI 87
84
TANG(J+IDSNXLPICCA1)+IDTANH2) - (IDSNXLPICCA1+IDTANH2) = (CDSSXLPICCA1+IDTANH2)
SLI 88
OPEACH=TANG(CPECA)
SLI 89
SINCIC=SINCIC
SLI 90
GC IC A1
SLI 91
85
CONTINUE
SLI 92
86
TAN(CIC) = TAN(CIC)
SLI 93
87
CONTINUE
SLI 94
88
SPH=SPH
SLI 95
CONTINUE
SLI 96
89
CONTINUE
SLI 97
90
CONTINUE
SLI 98
CONTINUE
SLI 99
CONTINUE
SLI 100
OPEACH+OPEACH + PIC
SLI 101
CONTINUE
SLI 102
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SLI 103
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SLI 104
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SLI 105
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SLI 106
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SLI 116
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SLI 117
CONTINUE
SLI 118
CCPLTE CALCPLOT PLOTTER DATA FOR PLOTTING TOPOGRAPHY OF SLICE
SLI 119
C AND GREAT CIRCLE ON VAN DER GRINN MAP
SLI 120
C RACPAP
SLI 121
RACPAP = 10.0000
SLI 122
CCNVR = INCH TO CM RATIO USED IN TOPOGRAPHY
SLI 123
CCNVR = 0.100
SLI 124
RINCH = ACINCH
SLI 125
RINCH = RINCH
SLI 126
RINCH = RINCH
SLI 127
RINCH = RINCH
SLI 128
RINCH = RINCH
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RINCH = RINCH
SLI 159
RINCH = RINCH
SLI 160
RINCH = RINCH
SLI 161
51
CONTINUE

CALL ANGLE (X,Y,ALPHA)
ALP=ALPHA+XMD
IF (ALP(2)) .GT. 360.000
CONTINUE

CALL TOPDGR (THEX,ALPHA,H)
PHI=PHI+F
CALL VDC (PHI,ALPHA,JMD,PSEC,NDEG,KG,YG)
THETA+100
V=1.0+10.0
WRITE (3,203) (X,Y),X,Y
WRITE (3,204) (X,Y),X,Y
CONTINUE

FINC PICCLE OF SYMPL/CCLER RANGE
SYMP+SYMP/2.0+C.TEU

COMPUTE NUMBER OF HORIZONTAL LINES IN MAP
KLOGIC+LLOG
LLOGIC=ILOGIC
ILOGIC=ILOGIC/10
IF (LLOGIC .EQ. 1) NLOGIC=10
NLOGIC=KLOGIC+1
NLOGIC=KLOGIC+1
RLOGIC=KLOGIC

FINC LEFT AND RIGHT LIMITS OF MAP BY CALLING CIRC
CALL CIRCRNCSEC

DC IC NUMMAP+1,1

INITIALIZE LINE VALUES
XMAP IS FOR PRINT-OUT PICTURE
IPI IS FOR DICPOED PICTURE
DC X=K+1,121
TPAPIK+ALPHA(11)

SPACE DOWN THE PAGE
WRITE (6,183)

PCPAPI (EID)
NSPACE+120
NSPACE+120
DC X=K+1,NSPACE
WRITE (6,184)

FINC THE RELATIVE DENSITY, DENSITY, OR DENSITY VARIATION CH EACH
HORIZONTAL LINE
DC X=L+1,RY
LDRY=LP+1
PL2=L2

KMAP=LOMN(LP,1)
KMAP=LOMN(LP,2)

CONTINUE

FINC THE XY,Z COORDINATES OF EACH POINT ON THE LINE
X+X+X+X+X
X+X+X+X+X
X+X+X+X+X
X+X+X+X+X

FINC THE SPHERICAL POLAR COORDINATES OF POINT
K=K+1

IS THE POINT IN THE CIRCLE
IF (R+R-RRMM) .GT. 3.0
CONTINUE

IS THE POINT BELOW THE CIRCLE
IF (R+R-RRMM) .LT. 3.0
CONTINUE

DEN+DEN+DEN+DEN
DC TC 103

52
102 CONTINUE
         X0Y5C0=TSORT(*2 + Y**2)
         IF (Z) 74,25,25
         THETA=PI/2
         GC IC 25
         24 U=XSORTZ
         THETA=CTAN(L)
         IF (Z) 44,25,25
         44 THETA=PI*PI
         20 CONTINUE
         CALL ANOL(90000)

C COMPUTE THE RELATIVE DENSITY/DENSITY OR DENSITY VARIATION AT POINTS
         CALL DENSITY(A,THETA,XLORD,NOEN,HDEN,JDEN)

103 CONTINUE
          CALL ANOL(F)
          C PUT THE RIGHT SYPOL/AUSPER IN XMAP(K)/IMAP(X)
          XSICEN/SCALE
          JNUP+SYPOL 4 XS
          IF (JNUP .LE. 0) JNUP+1
          If (JNUP .GE. PAXSVP) JNUP+MAX
          XPAPIKI - BETAI11
          3 CONTINUE
          C PRINT THE LINE
          WRITE (160141, (XPAPIPII))
          C WRITE 100 TO OVERLAY MAP. PERCMAP
          C PRINT THE LINE
          DC (K) XRMAP,GRMAP
          XPAPIKI + ALPHA(23)
          TPAPIKI - BETA111)
          3 CONTINUE
          10 CONTINUE
          RETURN
          END

SUBRUTINE VANDER (PKP,MAP,MPAP,RPAP)

C THIS SUBROUTINE COMPUTES THE RELATIVE DENSITY, DENSITY, OR DENSITY VARIATION ON A SURFACE OF CHOSEN RADII USING THE VAN DER GRINTEN PROJECTION.
C IT DIVIDES THE MAP INTO TWO HEMISPHERES TO MAKE THE MAP BIG ENOUGH TO OVERLAY CA PALL LEMAY'S TECTONIC ACTIVITY MAP.
C
C NTATION
C RRM = RADIAL DISTANCE OF MAP SURFACE IN KILOMETERS
C HPAP = TOTAL HEIGHT OF OVERLAY MAP IN CENTIMETERS
C NPAC = RADIUS OF PAP IN HORIZONTAL SPACES ACROSS THE PAGE (INCHES)
C
C SUBRTUTINES CALLED:
C 1. CIRC
C 2. CUBIC
C 3. DENSITY
C 4. QUARC
C
C NOTES
C 1. NPAC .LE. 102.
C 2. MAP .LE. 5.0 CM.

C FILE INPUT DATA (COLUMN 1 OF INPUT STARTS IN COLUMN 3 HERE)

SUBRUTINE VANDER (PKP,MAP,MPAP,RPAP)

C (FORMAT: A6)

UNIT   J=I-14)  (FORMAT: 1346,A2)  VAN 23
SURFACE PAP  VAN 26
NPAP  RRM  HPAP  WPAP  (FORMAT: 15.3F10.5)  VAN 27
102 6371.0 39.2 52.0  VAN 28
       IMPLICIT REAL*8(A-H,O-Z)
       INTEGER(2) XMAP(121), ETA(111)
       IMPLICIT REAL*4(A-H,O-Z)
       INTEGER(4) XMAP(121), ETA(111)

53
CIPENSICN ALPH121140
CIPENSICN AXP11211 VAN 31
CIPENSICN XDPENT1141 VAN 33
CIPENSICN/ILKAlXPAP VAN 35
CIPENSICN/ILKClFrPI•P12rPIEIYIrSCAIErNPHCfO.MAXSYr VAN 37
CIPENSICN/ILKhCeFr ALPMArLCWFI VAN 39
CIPENSICN/ILKh/NACAVD•RGCR/RLCWERrRUP VAN 41
CIPENSICN/FLKh/RE/DEN VAN 43
CIPENSICN/FLKh/OEfA VAN 45
CIPENSICN/FLKh/OEfA VAN 47
CIPENSICN/FLKh/OEfA VAN 49
CIPENSICN/ILKh/CEh,RE/DEN VAN 51
CIPENSICN/ILKh/CEh,RE/DEN VAN 53
CIPENSICN/ILKh/CEh,RE/DEN VAN 55
CIPENSICN/ILKh/CEh,RE/DEN VAN 57
CIPENSICN/ILKh/CEh,RE/DEN VAN 59
CIPENSICN/ILKh/CEh,RE/DEN VAN 61
CIPENSICN/ILKh/CEh,RE/DEN VAN 63
CIPENSICN/FLKh/RE/DEN VAN 65
CIPENSICN/FLKh/RE/DEN VAN 67
CIPENSICN/FLKh/RE/DEN VAN 69
CIPENSICN/ILKh/CEh,RE/DEN VAN 71
CIPENSICN/ILKh/CEh,RE/DEN VAN 73
CIPENSICN/ILKh/CEh,RE/DEN VAN 75
CIPENSICN/ILKh/CEh,RE/DEN VAN 77
CIPENSICN/ILKh/CEh,RE/DEN VAN 79
CIPENSICN/ILKh/CEh,RE/DEN VAN 81
CIPENSICN/ILKh/CEh,RE/DEN VAN 83
CIPENSICN/ILKh/CEh,RE/DEN VAN 85
CIPENSICN/ILKh/CEh,RE/DEN VAN 87
CIPENSICN/ILKh/CEh,RE/DEN VAN 89
CIPENSICN/ILKh/CEh,RE/DEN VAN 91
CIPENSICN/ILKh/CEh,RE/DEN VAN 93
CIPENSICN/ILKh/CEh,RE/DEN VAN 95
CIPENSICN/ILKh/CEh,RE/DEN VAN 97
CIPENSICN/ILKh/CEh,RE/DEN VAN 99
CIPENSICN/ILKh/CEh,RE/DEN VAN 101
CIPENSICN/ILKh/CEh,RE/DEN VAN 103
CIPENSICN/ILKh/CEh,RE/DEN VAN 105
CIPENSICN/ILKh/CEh,RE/DEN VAN 107
CIPENSICN/ILKh/CEh,RE/DEN VAN 109
CIPENSICN/ILKh/CEh,RE/DEN VAN 111
IF (JNUP .LE. 1) JNUP = 1
IF (JNUP .GE. 10) JNUP = 10

29 PRINT(1,ALPH,JNUP)
3 CONTINUE

C PRINT THE LINE

WRITE (14,(XPMAP(1),X=1,121))
14 FCPAT (56,121)
C WRITE FOR LOC.(XPMAP, K=1,121)
C 100 FCPOP (1,121)

C RESET THE LINE

DC 35 K-MIN,kMAX
XPMAP(1) = ALPH(121)
TPAFL = RETAIL1
15 CONTINUE

C 2 CONTINUE

C 10 CONTINUE

EOL VAN 129

SUBROUTINE DENSITY (R,THETA,ALPHA,NOEN,REFDEN,DEN)
DEN 1

C THIS SUBROUTINE COMPUTE THE RELATIVE DENSITY, DENSITY, OR
C DENSITY VARIATION AT A POINT INSIDE THE EARTH.

C

ACCLATION

R = RADIAL DISTANCE OF POINT FROM THE CENTER OF THE EARTH.
DEN 5

T=NUP = NORMALIZED TO THE EARTH'S RADIUS
DEN 6

T-NUP = COLATITUDE OF POINT IN MAYS
DEN 7

ALPHA = ANGLE OF POINT WITH THE X-AXIS, LYING IN THE X-Y PLANE
MEASURED IN RADIANS
DEN 8

DEN = RELATIVE DENSITY, DENSITY, OR DENSITY VARIATION AT THE
POINT
DEN 9

NOEN = 0 FOR RELATIVE DENSITY, =1 FOR ACTUAL DENSITY,
=2 FOR DENSITY VARIATION
DEN 10

SUBROUTINES CALLED:

1. LEGEND
DEN 11
2. CZIEWN (IF NOEN=1 OR NOEN=2)
DEN 12

IMPLEMENT REAL*8 (X, Y, Z)
DIMENSION CLM(36,37,21),CEE(36)
DIMENSION PARCH(121)
CCCPN/FRK/CLP+CEE
CCCPN/FRK/CLP+GJ,PI,PI,PICV2,SCALE,NPHOTO,MAPPY
CCCPN/FRK/LPM,LMAX,LLMAX,LUP
CCCPN/FRK/MAJAX,MNAX,PMAX,PMAX,PMAX
CCCPN/FRK/NAMAX
C C-ANCE VARIABLES FROM Theta TO PHI
DEN 13

P=1-PICV2 - Theta
DEN 14

C COMPT LEGENDE POLYNOMIALS
DEN 15

CALL LEGEND(PHI,LPHI)
DEN 16

C COMPUTE RELATIVE DENSITY
DEN 17

SUPERG.C,C,C
DC 5 L,L,PIN,LMAX
RL=RLPL
MAX_L = 1
DC 5 P=1,MAX
XP=1 = 1
ARG=XP+1
DEN 18

5+SIGMA+SIGMA
CC=CC:(ARG)
4
DEN 19

SUM-SUM+ (CLM(L,P+1,1)*CC + CLM(L,M+2,1)*P*P+1,1)*P*P+1,1)*P+

5 CONTINUE
DEN 20

C SEE IF ACTUAL DENSITY IS WANTED
DEN 21

IF (NOEN .EQ. 1) GO TO 7

C SEE IF DENSITY VARIATION IS WANTED
DEN 22

IF (NOEN .EQ. 2) GO TO 9

GC TC 0

7 CONTINUE
DEN 23

CALL CZIEWN (R,DEN)1
DEN=CENC51+0.01+DEN - MAPPY
DEN 24

GC TC 0

9 CONTINUE
DEN 25

CALL CZIEWN (R,DEN)1
DEN=CENC51+0.01+DEN
DEN 26

CONTINUE
DEN 27

RETURN
DEN 28
This subroutine computes the angle with the x-axis from the (x,y) coordinates of a point.

ACTATION

X = x-coordinate of point
Y = y-coordinate of point
XLMCA = angle with x-axis

SUBROUTINES CALLED
NONE

NOTES

1. XLMCA IS MEASURED IN RADIANS.
2. IF X=0 AND Y=0, THEN XLMCA=0.

SUBROUTINE ANGLE(X,Y,XLMCA)

END

This subroutine computes the normalized associated Legendre polynomials.

ACTATION

PHI = geocentric latitude in radians
NMAX = maximum degree and order of the polynomials
PRAM = array in which the polynomials are stored

SUBROUTINES CALLED
NONE

NOTES

1. Computes polynomials using Kaula's APMI normalisation.
2. NMAX IS LESS THAN OR EQUAL TO 100.
3. DIMENSION OF PHA IS 1+NMAX*(NMAX+1)/2.
4. POLYNOMIAL OF DEGREE N AND ORDER M IS STORED IN PRAM(INDEX).
5. SUBROUTINE HAS UNDERFLOW WHEN PHI IS NEAR THE POLES.

SUBROUTINE LEGCOT(PI1,NMAX,PRAM)

END

This subroutine computes the normalized associated Legendre polynomials.

ACTATION

PHI = geocentric latitude in radians
NMAX = maximum degree and order of the polynomials
PRAM = array in which the polynomials are stored

SUBROUTINES CALLED
NONE

NOTES

1. Computes polynomials using Kaula's APMI normalisation.
2. NMAX IS LESS THAN OR EQUAL TO 100.
3. DIMENSION OF PHA IS 1+NMAX*(NMAX+1)/2.
4. POLYNOMIAL OF DEGREE N AND ORDER M IS STORED IN PRAM(INDEX).
5. SUBROUTINE HAS UNDERFLOW WHEN PHI IS NEAR THE POLES.

SUBROUTINE LEGCOT(PI1,NMAX,PRAM)

END
IF TO F(11) 9,4,11
C  REGION G
9 CENFZ=1.595950C = 7.2554400R
GC EC 19
10 CONTINUE
CIF IF - F(11) 11,21,12
C  REGION G
11 CENFZ=1.595950C = 7.2554400R
GC EC 19
12 CONTINUE
CIF IF - F(11) 13,13,14
C  REGION G
13 CENFZ=1.595950C = 7.2554400R
GC EC 19
14 CONTINUE
CIF IF - F(11) 15,15,16
C  REGION G
15 CENFZ=2.0020000
GC EC 19
16 CONTINUE
CIF IF - F(11) 17,17,18
C  REGION G
17 CENFZ=2.0020000
GC EC 19
C  REGION GC
18 CENFZ=1.0300000
19 CONTINUE
RETURN
THE SPACE IN WHICH THE CIRCULAR-SHAPED MAPS START AND STOP ON A PARTICULAR LINE.
ADD
SUBROUTINE TCPCCR (THE1,XMLCA,H)
STOP 2
THE SURFACE OF THE EARTH.
STOP 3
ACTATION
STOP 4
THE1A = COLATITUDE OF POINT IN RADIANS
STOP 5
XMLCA = ANGLE OF POINT WITH THE X-AXIS, LYING IN THE X-Y PLANE;
STOP 6
H = TOPOGRAPHIC HEIGHT IN KILOMETERS
STOP 7
SUBROUTINES CALLED
STOP 8
1. LEGEND
STOP 9
4. DETERMINE EQUATORIAL POLYAODES
STOP 10
CALL LEGEND (PHI, LMAX)
STOP 11
C DETERMINE TOPOGRAPHIC HEIGHT IN KILOMETERS
STOP 12
G = 0.0003
STOP 13
G = MAX + 1
STOP 14
A(0) = 1
STOP 15
A(0) = LMAX
STOP 16
N=0
STOP 17
N=0
STOP 18
SUM = SUM + (1TOPCLI+1.1)*CC + (2TOPCL(M1,2)+55)*(PRAMC0)
STOP 19
CONTINUE
STOP 20
END
STOP 21
SUBROUTINE CIRC(RADX azi)
C
C THIS SUBROUTINE COMPUTES THE SPACES IN WHICH THE CIRCULAR-SHAPED MAPS START AND STOP ON A PARTICULAR LINE.
C
C ACTATION
C
C RHOSEC = RADIUS OF CIRCLE, MEASURED IN HORIZONTAL SPACES
C N=1 = ARRAY IN WHICH THE MAP STARTS AND STOPS ON A PARTICULAR LINE IS STORED
C LMAX=1 = ARRAY IN WHICH THE MAP STARTS AND STOPS ON A PARTICULAR LINE IS STORED
C
SUBROUTINES CALLED:

ACNE

NOTES

1. LCW11 (LP.11) STORES THE SPACE NUMBER WHERE THE MAP STARTS ON LINE LP.4 AND LCW11 (LP.21) WHERE IT STOPS (INCLUSIVE).

2. ALL MAPS ARE CENTERED ON SPACE 61.

[Numerous lines of code follow, including a subroutine called ACNE.

NOTES

1. FOR FURTHER DETAILS SEE O.P. RUMINCAP, "INVERTING X,Y GRID COORDINATES TO OBTAIN LATITUDE AND LONGITUDE IN THE VAN DER GRINTEN PROJECTION", MASS TP 4796, AUGUST 1980.

2. S+2MII0 IN THE NOTATION OF THE PAPER CITED.

[Numerous lines of code follow, including more subroutine calls and notes.

Page 89]
CALLOUT EUCEHCEX(9.5,LMCA)

CC THIS SUBROUTINE COMPUTES THE LENGTH OF A POINT FROM ITS 
CC X-Y COORDINATES IN THE VAN DER GRAAF GRANTEN PROJECTION.
CC
CC ACTATION
CC
CC X = X-COORDINATE OF POINT
CC Y = Y-COORDINATE OF POINT
CC S = SCALE LENGTH OF MAP, EQUAL TO 100 DEGREES OF 
CC LONGITUDE MEASURED ALONG THE EQUATOR
CC XLMCA = LONGITUDE IN RADIANS

SUBROUTINES CALLED:

ACNE

NOTES

1. FOR FURTHER DETAILS SEE D.P. RUSINGA, "INVERSION X-Y GRID 
COORDINATES TO EARTH LATITUDE AND LONGITUDE IN THE VAN DER 

CC

CC APPLICIT REALX(1=A-H,0-Z)

P=3.14159265358979

1 IF (X - 9) 21:2

1 XLMCA=0.0000

2 CONTINUE

2 X=999

2 Y=999

2 S=545

2 S=5452

2 R2=256 + 2.000052*(X-9) + (X + 2)*999

2 ELL=92 + Y2 - 52 + 0.004/100/10/3.00009

2 XLMCA=ELL/PI

10 CONTINUE

RETURN

END

0 SUBROUTINE VGC (PHI,KLMCA,RADPAP,NDEG,X,Y)

CC THIS SUBROUTINE COMPUTES THE X,Y GRID COORDINATES OF A POINT 
CC IN THE VAN DER GRAAF GRANTEN PROJECTION FROM ITS LATITUDE AND LONGITUDE.
CC
CC ACTATION

CC PHI = LATITUDE OF POINT (IN DEGREES OR RADIANS)

CC KLMCA = LONGITUDE OF POINT (IN DEGREES OR RADIANS)

CC RADPAP = RADIUS OF MAP

CC NDEG = 1 IF PHI AND KLMCA ARE IN DEGREES; 0 IF IN RADIANS

CC X = X GRID COORDINATE

CC Y = Y GRID COORDINATE

SUBROUTINES CALLED:

ACNE

NOTES

VGC 0 13
1. The Greenwich Meridian (XLMDA=0) runs down the center of the map.
2. The Origin X0, Y0 of the grid coordinate system is located at the center of the map (XLMDA=01).
3. If the absolute value of ELL or ELL, i.e., EPSLON, then the value is assumed to be zero. This is done to avoid infinities.

```fortran
IMPLICIT REAL*8 (A-H,O-Z)
PI=3.1415926535897932
EPSLCN=1.00E-10
IF (XLMDA .EQ. 1) CO TC 1

10 ELL=XLMDA/180.000

1 CONTINUE

G C T C 1

10 CONTINUE

1 EXE
```

2531 CARDS