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ORBITAL FLUX INTEGRATIONS WITHIN THE SUBSYNCHRONOUS REGIONS OF THE GEOMAGNETIC CAVITY

Part 1

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SUMMARY

A computer code to calculate omnidirectional vehicle encountered trapped particle fluxes has been developed. With it, fast and accurate orbital flux computations can be performed for arbitrary circular or elliptical trajectories within the geomagnetic cavity bounded by L=6.6 earth radii. The method of calculating the trapped particle intensities, the geomagnetic field models employed in obtaining the magnetic coordinates B and L, and the models of the radiation environments used in the flux calculations are presented. Solar cycle effects on the belts and other time dependent variations in the proton and electron populations are briefly examined. The decay of the artificial "Starfish" component of the electron environment is considered. Finally, limits and limitations of models, stepsize and duration of calculations, and other methods of computation are discussed.

1. INTRODUCTION.

Since the first satellite observations of trapped radiation and especially since the "STARFISH" experiment over the Pacific on July 9, 1962, which resulted in the injection of about 10^{27} high energy electrons into the upper atmosphere, it had become apparent that fast and reasonably accurate methods were needed for estimating the radiation hazards, to which satellites would be exposed, initially mainly on low and medium altitude missions. To meet this demand, attempts were made at Goddard Space Flight Center as early as 1962 to write computer programs for the obtainment of flux estimates. Gradually, as the composition and population of the radiation belts became better understood and satellites penetrated deeper into space, faster and more accurate routines were developed, which reflected and utilized the added knowledge and which ultimately extended their effective range up to and including the synchronous altitude. The Orbital Flux Codes (OFC's) of today are flexible, fast and efficient tools for the reliable calculation and valid prediction of expected radiation levels of any orbital configuration in near earth space to an equatorial distance of 6.6 earth radii. The following sections will outline the basic functions of the OFC's and the method employed in the flux calculations.

2. STEPS IN THE CALCULATION OF ENERGETIC PARTICLE FLUXES.

The calculation by the OFC's of energetic particle fluxes encountered by satellites in elliptical or circular orbits within several earth radii may be divided into three phases.

Phase A: The orbit determination phase which generates an orbital tape containing the geocentric coordinates of successive points along the trajectory at arbitrary constant time intervals ∇t (see section 6,A). This part of phase A is not included in the OFC's. It is left to the user to select his own method of generating the orbit and to decide on the accuracy of the process involved. To obtain a useful estimate of the radiation level encountered on long flights, it is recommended that their tapes contain at least a 24-hour sample of the orbit (see section 6,B).

After the generation of the orbital tape the trajectory is transferred point by point into magnetic B-L space,* using McIlwain's coordinate transformation routine INVAR (1) (see section 3,C). This transformation could be combined with the orbit determination, if so desired.

Phase B: The actual orbital flux computation is now performed. For every point along the trajectory the instantaneous flux is obtained through interpolation from a tabulation of the radiation intensities ϕ_i in B-L space. The flux is then orbit-integrated over the given duration T of the flight by a numerical quadrature process to yield the total number J_T of particles incident on one square centimeter of surface. For purpose of calculation, T is divided

*B is the field strength (in gauss) at a given point on or above the earth's surface and L is the magnetic shell parameter (in R_e) which labels the field line passing through that point. L is defined as the geocentric distance of the equatorial intersect of the field line and is approximately constant along a line of force (±1%).

into N equal subintervals ∇t, giving

$$J_T = \sum_{i=1}^{N} \phi_i(B,L)\nabla t \qquad 1$$

or

$$J_T = \nabla t \sum_{i=1}^{N} \varphi_i(B,L) \qquad 2$$

Equation 1 is used if intermediate output is required; otherwise the form 2 is preferred.

For electrons near the earth's surface the slowly decaying radiation produced in 1962 by the "STARFISH" explosion gives a significant contribution. In such cases, appropriate decay factors are applied at every step, updating the flux to the desired epoch (2) (see section 3).

Throughout the calculation, the values of several variables and parameters are obtained and stored for later use in phase C, including:

a) Flux peaks in each orbital period with their position in geocentric and magnetic coordinates and the elapsed orbital time at which they occur,

b) The total accumulated fluxes in each orbital period,

c) A breakdown of encountered fluxes into about 8 intensity ranges with duration of exposure, and

d) The distribution of the fluxes into several ranges of the parameter L.

Phase C: This is the output phase and deals mainly with the manipulation and arrangement of the data computed in phase B and produces a tabulation of radiation intensities. Thus, averaging factors are computed and applied (per day, per orbit, etc.), spectral distributions are calculated, results are tested and checked. All output is properly labelled and information pertinent to the orbit itself is printed as well.

3. ENVIRONMENTAL AND GEOMAGNETIC MODELS CURRENTLY IN USE.

Orbital flux calculations in near earth space will be influenced by three major factors: a) the choice of the flux grids, b) the model of the geomagnetic field representation used in the computation of the magnetic coordinates B and L, and c) the method of obtaining B and L. This is true for protons and electrons alike.

A. Flux Grids: The best studies presently available on the radiation belts of the earth are by Vette (3) and King (4) for protons and by Vette (5) for electrons. These documents reflect most of the radiation belt observations available to date and the models they describe are presented by means of radiation intensity "maps". A special study by Vette (6) for the synchronous altitude electrons supplements the environmental models.

The respective composite electron maps AE2, AE3 and the proton maps AP1, AP2, AP3, AP4, AP5 are nowadays widely used in flux calculations. In the OFC's, the earlier electron map AE1 (3) has been replaced by the more recent AE2 (5).

B. Geomagnetic Field: There exist several models describing the geomagnetic field in terms of harmonic expansion coefficients of the scalar geomagnetic potential. These field models are constructed by fitting a varying number of spherical Lengendre coefficients to actual surface measurements. Periodic recomputations of the coefficients are necessary to take into account the increased knowledge of the field and its secular changes. In order to facilitate meaningful comparisons of data and results, especially in trapped particle studies, the 48-term Jensen and Cain model for 1960.0 (7) was selected in 1963 for general use, in conjunction with tests of B-L computing codes, discussed in paragraph C.

In 1966 a 99-term recomputed version of the 1960.0 field was published by Hendricks and Cain (8), which appears to be more accurate and may well be adopted as the new standard.

C. B-L Coordinates: Computer codes for deriving B and L with different field models were tested in 1963 at Goddard Space Flight Center and McIlwain's routine INVAR (version of 1962) was proposed for standard and uniform use on the basis of speed, accuracy and general applicability. The field used in INVAR is the 48 term expansion by Jensen and Cain of 1960.0 (7). The average error in B and L, computed with this model, does not exceed $2X10^{-3}$ gauss, i.e. 200 gammas for the former and about 1°/o for the latter.

A new modified and faster version of INVAR is now available through the National Space Sciences Data Center of Goddard Space Flight Center. It gives the user a choice between the 48-term Jensen and Cain fit of the earlier code and the new set of 99 coefficients by Hendricks and Cain for the same epoch.

Stern (10) has proposed another interesting method to calculate the magnetic shell parameter L, with almost no restrictions to its applicability at the polar or equatorial regions. It seems to be considerably faster than INVAR but is not as accurate.

4. PHYSICAL PROCESSES CONSIDERED.

Time dependent changes in the trapped particle environment are of importance in long range flux predictions. While the slow solar cycle variations in the energetic proton population at low altitudes are not well determined, they may be neglected since the total radiation dose from this source is relatively small.

However, the rate of change of the electron flux is far more rapid and significant and hence of real concern in orbital flux calculations. There are two processes involved. First, there is a decrease with time of the inner belt electron levels ($L<1.7$), resulting from the continuing decay process of the Starfish population, that requires an updating of the AE2 fluxes by suitable decay factors. These are calculated from experimentally measured decay constants by a special routine (2) developed in 1964 and modified in 1966.

Because they change with time, the decay constants now in use are slowly becoming obsolete. Moreover, the lifetimes of the Starfish remnants are becoming shorter and the decay rate is expected to accelerate with the approach of solar maximum, so that the electron population will decrease faster than predicted by the computations.

It is evident that continuous measurements of the decay constants are necessary, at least for the next 2 or 3 years. After the 1969 solar maximum, the electron fluxes in the $L<1.7$ region will probably revert back to their natural levels. Their fluctuations due to the solar cycle will then have to be determined experimentally.

Secondly, there is a substantial rise predicted in the flux levels at $2<L<4$ for solar maximum. It is anticipated that the intensities of the outer belt electrons will go up because of increased activity on the sun (magnetic storms). However, instabilities in the outer zone due to field line loading would impose limitations on the amount of the added number of particles trapped in that way. At the time of this writing, estimates based on the 1964 levels varied from a factor of 50 to a factor of 280 (5), with the greatest increase placed at about L~3.5.

5. LIMITS OF THE ENVIRONMENTAL MODELS

Most available models of the radiation belts surrounding the earth confine themselves within a magnetic space bounded approximately by L=6 and B=.60. The reason for this is that at about 6.5 earth radii (the altitude of synchronous satellites) fluxes will be extremely variable in time, with irregular changes from day to day. Solar proton events are expected to penetrate this region with almost undiminished strength. Also the magnetosphere at that altitude is compressed on the day side and elongated on the night side, due to the solar wind, and becomes markedly asymmetrical.‡ This means that the indicated values of B and L may be regarded as the limits of the ordered distribution of those trapped particles that are not affected by large temporal or diurnal variations.

In particular, Vette's proton maps (3) contain no significant information beyond L=4.5 and B=.32. Although in special cases the maps may be used beyond these values, it was found that the contributions to the orbital flux calculations derived from such an extension were at times insignificant and at other times produced dubious distortions in the calculated flux profile, depending on the configuration of the orbit.

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‡ In magnetic fields strongly departing from axial symmetry it is no longer possible to assign a single value of L to each field line. A group of particles trapped in such a field, starting from the same field line on the day side but with different mirror points on this line, will usually have drifted to a wide range of field lines when they have reached the night side. If a magnetic shell parameter "L" is to be assigned to field lines in such a field, a different assignation is needed for each group of particles, depending also on the field intensity B_m at which they mirror. In practice, no such assignation exists, and radiation intensities observed in this region resist any attempt of classification. (9)

It is believed that this is mainly due to the extrapolated exponential energy parameters in the higher L regions. Therefore, the values of L=4.5 and B=.32 have been incorporated into the OFC's as the boundaries for proton calculations.

With respect to electrons, the meaningful part of the AE2 map does not extend significantly beyond L=6.2. The limits of this map have been placed at L=6.5 and B=.60 for computational convenience.

6. TIME CONSIDERATIONS

There exist two effective ways by which the total computing time of the OFC's may be controlled and the accuracy of the results influenced. These are a variation in the size of the interval ∇t or a modification of the duration of the orbit sample T. A third possibility, not available in the codes, will be discussed briefly in section 7.

The stepsize ∇t: Convenience and speed made it originally desirable to have the time interval ∇t constant rather than variable, but with minor modifications in the programs a varying interval might be substituted.

The size of the constant ∇t is a matter of preference of the user and may be determined by him. However, there are certain considerations which will restrict this choice. On the one hand, the spatial distribution of trapped particles is not even or symmetric; large gradients in the fluxes occur near the magnetic anomalies. As a consequence, too big an interval, while substantially decreasing the number of points per orbit and hence saving computer time, may result in the possibility of entirely missing a high intensity region, which will cause the calculations to be inaccurate and the results misleading. On the other hand, too small an interval, while improving accuracy, will also considerably increase computer time.

Experience has shown that for orbits within 3 earth radii a 1 minute interval will satisfy the requirements for speed and accuracy reasonably well in the majority of cases. This stepsize is now most commonly used in orbital flux calculations. For especially precise computations a 14 second interval is favored by the writer.

The flight duration T: The simulated duration of the orbital flight sample is controlled by the input quantity T. Through T a run may be terminated at any desired length. In selecting an appropriate value for T the user is again faced with the problem of available computer time versus satisfactory and realistic results. Because of the rotation of the earth under the satellite trajectory and the precession of the orbit due to earth-mass anomalies, the vehicle sweeps out a tube in geomagnetic space.

To assure a truly representative sampling of the ambient radiation environment in that tube and to obtain a meaningful average, it is necessary to extend the flux calculations over an adequate length of flight time. This means that for most orbits the flight duration should not be less than 24 hours. If very elliptical trajectories are investigated or if the orbital period of a vehicle exceeds 100 minutes, it may be advisable to extend the duration to 48 hours or more.

A balanced adjustment of both parameters, ∇t and T, will optimize the running time for a given accuracy.

7. OTHER METHODS OF COMPUTATION

Many independent programs for orbital flux calculations have been written, some quite elaborate, reliable and effective; they were mostly developed along similar lines as the OFC's and they usually work on parallel principles, the method being more or less the same.

Several workers have also tried to produce computer programs which greatly reduce the amount of computer time required. To this end, some have deliberately introduced such approximations that the program produces essentially a rough estimate only of the encountered fluxes. Care should be taken therefore when using any <u>fast</u> routines unless one is familiar with the method used by them.

However, there is another way of increasing the computational speed, which does not reduce accuracy. It is based on the assumption that certain regions of space do not enter into orbital flux considerations at all because of the geomagnetic geometry. One could define these regions as being that part of space, which lies outside the L=6.6 shell. Since the approximate boundaries of this shell in geocentric polar space are reasonably well known, a series of tests of the geocentric coordinates of a point would determine if it is of significance for the flux calculations. In this case, and only then, a transformation to B-L coordinates would be performed. This scheme would be faster than the OFC's mostly for polar or high inclination orbits where up to 50°/o of the points may lie outside the critical regions, depending on the altitude and the orbit configuration.

8. CONCLUDING REMARKS

Since 1962, orbital flux calculations have become an increasingly important factor in the planning of missions and in the designing of spacecraft or equipment.

Many specific cases have occurred, where orbital flux calculations have helped in the evaluation of data, have assisted in the interpretation of observed phenomena or in the clarification of recorded events, and have contributed to the assessment of component degradation, failure or damage.

Strong interest is continuously expressed in them and a growing number of requests for routine or special radiation environment studies is being received. The fulfillment of these requests has guided the development of the OFC's in the past. Requests, imposing requirements of constantly rising complexity and sophistication, necessitated many improvements and resulted in a multitude of changes and additions.

In the near future, a fusion of all programs into one unified master routine may be attempted. It is also planned to eventually include 1 Mev equivalence calculations for as many materials as possible, depending on the availability of damage curves, and to add dosage conversion.

The major emphasis, however, will be placed, as before, on the periodic updating of the codes. It is hoped that in 2 or 3 years sufficient new information and data will have been collected, to permit the construction of reasonable solar cycle dependent models of the environments.

The OFC's in their present form compute integral fluxes and integral-flux-differences but, with only slight changes, differential fluxes or other useful quantities may become available.

Input parameters permit the selection of either of the geomagnetic field models mentioned in section 3b and control the intermediate or running output for every nth position along the trajectory (n=0,1,2,3.....).

When n is not zero, the program prints the geocentric and the magnetic coordinates of every nth point, the time associated with it, and the instantaneous or positional flux in the decayed and non-decayed form. It also gives the continuous summation value at that position.

The field computing part of the program has been kept separate in the form of a subroutine. This is a practical and advisable arrangement, because it is most convenient for interchanging or updating the various models. Similarly, the environmental models are contained in separate subroutines for the same reasons.

The codes, initially written in FORTRAN IV for the IBM 7094, DCS System, have been recently modified into FORTRAN H for use on the 360.

9. PART 2

Part 2 of this work is planned for publication in late summer, 1967. It will present extensive computational results, which will be analysed, discussed and interpreted. It will also include complete listings and flow charts of the codes with proper instructions and explanations.

Finally, world maps depicting contours of constant flux at selected altitude levels will be attached.

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