Shading evaluations with general three-dimensional models

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The SHADOWPACK package of computer programs has been developed to facilitate shading evaluations, for the direct component of solar radiation, with general 3D models. An interactive solid modelling program allows the user to construct and view the 3D model before saving it for further analysis and display. Other programs permit the graphical display of the shading situation throughout the year, the quantitative assessment of energy received on different faces of the model, and the display of the distribution of energy received on particular faces by means of contour plots. The use of the computer graphics approach has proved particularly convenient because of the similarity between the techniques used for graphical and numerical algorithms.

shading evaluation, 3D models

A package of computer programs has been developed to facilitate shading evaluations for the direct component of solar radiation, with general, 3D models. Shading studies are important in passive solar design, general building design, and in choosing the locations of components such as Trombe walls, solar panels and windows. Most previous approaches to shading evaluation have concentrated on the effects of particular features such as overhangs and side fins, eg the work of Jones[1] or Utzinger and Klein[2], or have made use of sunpath diagrams and shading masks[3,4]. With greater computing power now becoming readily accessible to researchers and engineers it is reasonable to use a general 3D modelling approach which can handle both simple and more complex situations. Several comprehensive systems for architectural energy simulation have been developed which include facilities for shading evaluations[5,6], and the effects of variable foliage density have also been treated[7]. However, work at the Joint Research Centre on solar components and energy auditing of existing buildings has shown that there is scope for the use of a simpler, less comprehensive, tool for quick display and evaluation of shading situations using 3D models.

The package described here allows the user to first construct the 3D model, using the interactive, solid modelling program ICON. The model description can then be written to a data file for subsequent analysis and display by four other programs. The names and functions of the programs are summarized below:

- ICON, for interactive construction of the 3D model
- SHADVIEW, to display shading for a particular day and sequence of times
- SHADYEAR, to display shading sampled through the whole year
- SHADEN, to calculate the direct energy received on particular faces, or all faces of the model
- ISOSUN, to plot the distribution of direct radiation received over a particular face, or over the ground

The use of the computer graphics approach has proved to be particularly convenient, not only for displaying the shading situations at different times, but also for checking that the calculation algorithms were functioning correctly. The development of the programs has been made easier by the fact that the algorithms used in the shading calculations have much in common with the display of shaded areas algorithm. The graphical display of shaded areas, therefore, gives an immediate visual check on the numercial calculations.

DATA STRUCTURE ALLOWING FOR HOLES

The data structure used for the 3D model specification consists of lists of vertices, lines, and polygonal faces. Each face can have any number of polygonal holes in it.

The hidden line removal and shading algorithms in the programs take account of the presence of holes. This is done by modifying the inclusion test (ie the test for inclusion of a point within a polygon) to first test for inclusion within the outer boundary, and then test for inclusion in the holes (if there are any). If a point is found to lie within any of the holes it is regarded as not being included.

Naturally a hole cannot cast a shadow or receive a shadow. It is, however, possible to calculate the energy passing through a hole by treating it as if it were a receiving plane. An example of holes used to simulate windows is given in Figure 1.

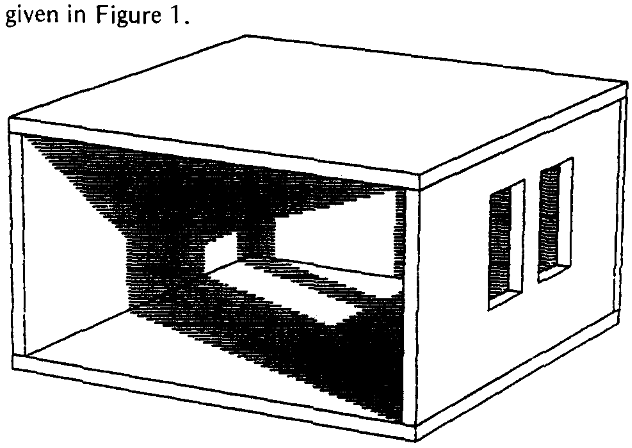

Figure 1. Example showing 'holes' used to represent windows

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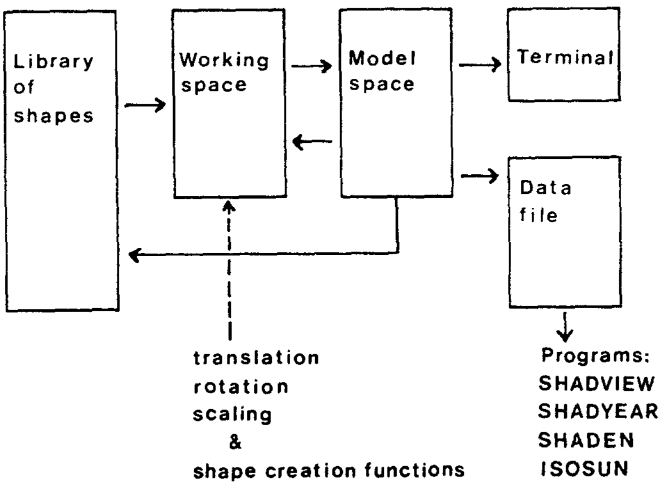

Figure 2. Operation of the program ICQN

The vertices defining the polygonal boundary of a face are always specified in a clockwise direction when viewing the face from the outside in order to allow the definition of the normal to the face without ambiguity. The direction of the face normal is required by the programs SHADEN and ISOSUN for calculating the energy received, and is also useful in speeding up the shading algorithms because it gives an immediate test of whether a whole face is self-shaded or not. All the shape creation subroutines in the program ICON ensure that the vertices are specified going around the polygonal faces in the correct sense.

ICON

ICON is an interactive program for the creation of 3D models. The program is oriented towards the modelling of buildings for shading and solar energy studies, but could also be applied in other areas where 3D models and their visualization are required.

A library of basic shapes can be accessed and these shapes can be scaled, rotated or translated in 3D before being added to the model. The model itself can be viewed in perspective at any stage during its construction, with or without hidden line removal, or with shading. The shading pattern generated is that corresponding to the direct solar radiation for a chosen latitude, time and day of the year.

In addition to using the library of basic shapes the program also has subroutines for the creation of certain geometrical forms by entering the appropriate parameters. These forms include irregular polygonal faces, prisms of polygonal cross section, cylinders, spheres and surfaces of revolution. Facilities for other forms can be added as they become necessary.

Once created the model can be added to the library of shapes or written to a separate data file for use by the other four programs.

The operation of the program is shown schematically in Figure 2. Solid arrows in the diagram show the direction of information flows. The diagram shows:

- the library of shapes
  - a direct access data file in which the specifications of the basic shapes or 'elements' are stored, each element is numbered and given a title
- the working space
  - an area of storage in which elements can be scaled, rotated or translated in 3D before being added to the model, elements can also be created in the working space, using the shape creation routines provided, and then manipulated as necessary
- the model space
  - an area of storage in which the model is built up by adding elements from the working space, both the model space and the working space can contain up to 1000 vertices, 1500 lines and 1000 faces; the model itself can be returned to the working space for manipulation and scaling
- the terminal
  - a device through which commands are entered and on which the model is displayed
- data file
  - a sequential file in which the final model can be stored for subsequent use by other programs

The program presently provides 26 commands which can be used in the model building process. All commands consist of three alphabetic characters, and after entry of a command the terminal displays a prompt message asking for whatever information is needed (if any) to complete execution of the command.

The commands can be classified into five types depending on their function. They are summarized below.

The transfer commands are as follows:

- GET takes an element from the library and transfers it to the working space, or copies the model itself from the model space to the work space
- ADD adds the element in the work space to the model, eliminating duplicate lines and vertices in the process
- REP adds the element in the work space to the model repeatedly with a given offset in three dimensions
- WRI writes the model to the sequential data file
- CAT catalogue; writes the model to the library of shapes

The manipulation commands operate on the element in the working space and are as follows:

- SCA scales the element in 3D
- MOV moves the element in 3D
- RTX, RTY, RTZ rotate the element about the x, y or z axis, respectively

Shape creation commands create shapes in the working space and are:

- POH, a horizontal polygon at $y = 0$.
- POV, a vertical polygon at $z = 0$.
- PRY, a prism parallel with the y axis.
- PRZ, a prism parallel with the z axis.
- SPH, a sphere, or upper segment of a sphere, centred on origin.
- CYL, a cylinder along the y axis.
- SRV, a surface of revolution; creates the surface obtained by revolving a curve about the y-axis. If the curve is closed a toroidal form will be obtained. The curve can be entered manually point by point or it can be a circle

The display commands are as follows:

- SHW displays the model as a 'wire frame' diagram (without hidden line removal)
- SHA displays the model with hidden line removal; also with shading if necessary

- VEP changes viewing parameters (azimuth, elevation and distance from origin of viewing position)
- SHP changes shading parameters (x-scanning interval, y-scanning interval, latitude, month, day and hour for sun's position)
- LST displays the geometrical specification of the model on the screen, ie the lists of vertices, lines and planes.

Finally, there are several miscellaneous commands:

- CLR clears the model space
- SIZ displays the number of vertices, lines and faces occupied by the element in the working space and by the model
- TEL titles of elements; lists of numbers and titles of all elements in the library
- END terminates the session

PROGRAMS SHADVIEW AND SHADYEAR

The program SHADVIEW creates views of the model and shadows, as seen from a chosen viewpoint, at regular intervals of time on a chosen day of the year. The other program, SHADYEAR, creates similar views sampled throughout the whole year; the days June 21st, September 21st (also equivalent to March 21st) and December 21st are chosen, and the shadows are drawn for times separated by 2-hour intervals through the day. The layout of the plots from SHADYEAR is designed to give an impression of the shading situation throughout the whole year on a single sheet of paper. Thus SHADVIEW is useful for detailed studies, while SHADYEAR gives the overall situation.

The determination of shaded areas is performed by scanning every face whose normal has a positive z' component, and determining whether each scan point is seen from the viewers direction, and shaded from the sun.

Each scan point represents a 'pixel' of dimensions given by the scanning step. If the scan point is both seen from the viewers direction and shaded from the sun, then the whole pixel is regarded as shaded. Greater accuracy can be achieved by using a finer scanning step. The stages involved in this process are summarized below:

- for the chosen latitude, day and time, calculate the azimuth and elevation of the sun[8]
- transform the coordinates of all vertices to a new system x'', y'', z'', in which the z'' axis points towards the sun, and store them
- perform the following steps for each face of the model:
  - test the sign of z' component of the face normal in the (x', y', z') system. If the z' component is less than or equal to zero, the face cannot be seen, so proceed to next face, else proceed with next steps

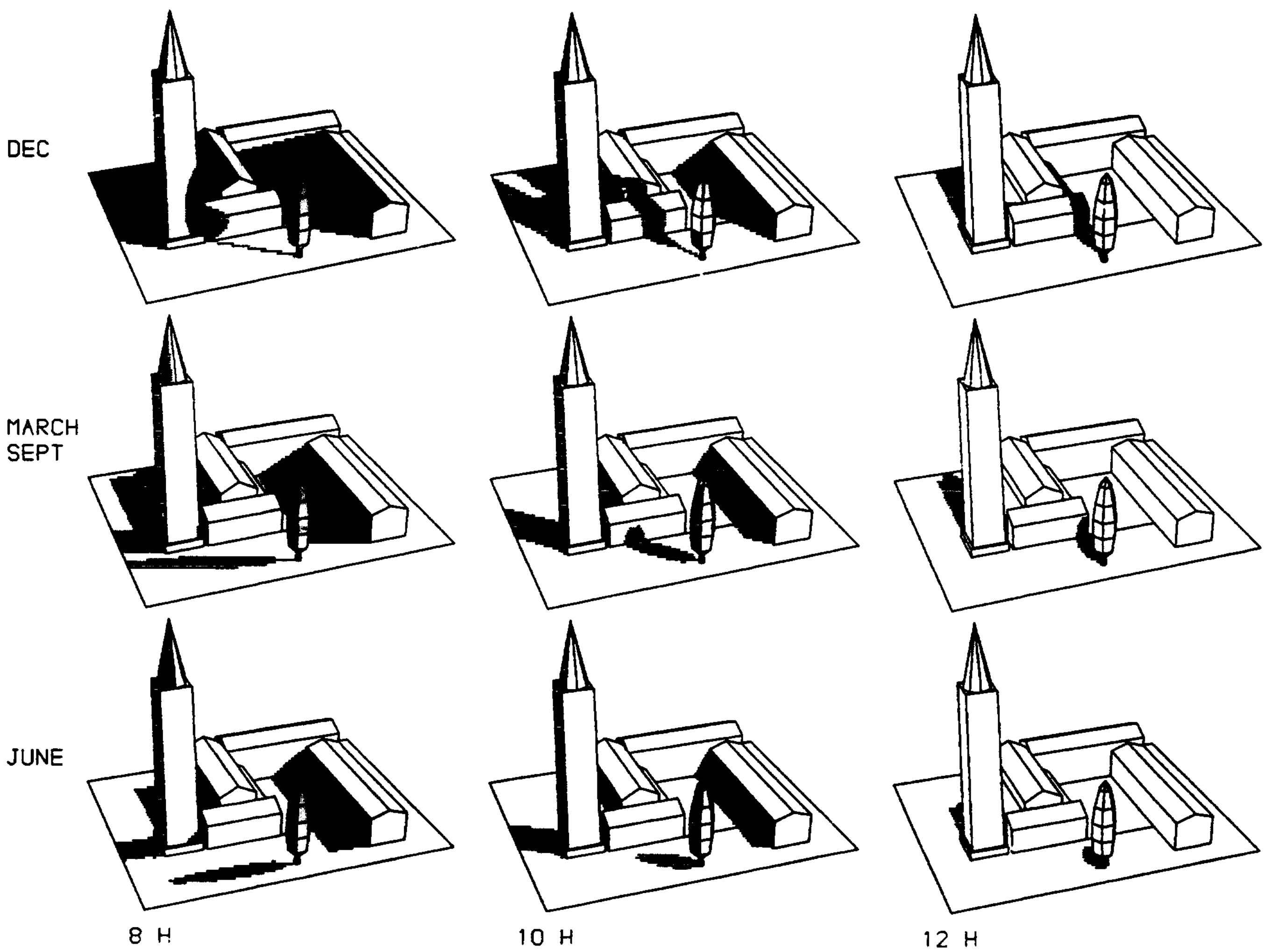

Figure 3. Example output from program SHADYEAR. The full output has two further columns of diagrams for 1400 h and 1600 h

- ○ scan the face in the coordinate system (x', y') for each scan point determine whether it is seen from the viewers direction by using the inclusion test and the z' distance test. If the scan point is seen then proceed with next steps
- ○ test for self shading using the z'' component of the face normal in the (x'', y'', z'') system. If shaded go to the final step
- ○ test for shading by other planes using the inclusion test and distance test in the coordinate system (x'', y'', z'')
- ○ if the scan point is shaded then shade the appropriate pixel

The second and fourth steps of the checks for each face are speeded up by using the same method. That is to say: once a scan point has been found to be hidden from the viewer, there is no point in going on comparing it with other faces, or, indeed, in checking whether it is shaded or not. Similarly, once a scan point has been found to be shaded, no further shading tests are made for that point. Extreme values for each face in both the coordinate systems x', y' and x'', y'' are also used to make preliminary inclusion tests before using the complete inclusion test.

Both programs, SHADVIEW and SHADYEAR, use the methods described above. The differences between the two lie only in the days and times for which results are produced and in the layout of the drawings. An example output from SHADYEAR is shown in Figure 3.

SHADEN

The program SHADEN calculates and tabulates the amount of direct solar energy received on any face, or any number of faces, of the building model. The results are tabulated on a monthly basis, and also summed to find the yearly totals. The weighted sum of the energies received on the different faces can also be calculated; thus, if the weights correspond to the surface areas of the different faces, the total direct energy received by the building can be found.

In order to save computing time the calculations are not made for every day of the year but sampled at one week intervals. This is possible because the declination of the sun changes only slowly with time (3°/week at the most). The 4th, 11th, 18th and 25th day of each month are chosen, and the average of the energy received on these four days is scaled by the number of days in the month. The sampling interval through the day is fifteen minutes.

The procedure for determining the energy received on the faces of interest is summarized as follows:

- (1) calculate the azimuth and elevation of the sun
- (2) calculate the intensity of direct solar radiation, I KW/m^2. This is done assuming clear sky conditions[8], or by interpolating hourly Test Reference Year (TRY) data
- (3) transform the model coordinates to a new system x'', y'', z'', in which the z'' axis points towards the sun; the coordinates x'', y'' thus give the projection of the model as seen from the sun's direction
- (4) test the face of interest for self-shading by testing the sign of the z'' component of the face normal. If shaded go to step (8), otherwise continue with next steps
- (5) scan the face of interest in the coordinate system x'', y''; for each scan point determine whether it is shaded or not, for a scan point to be shaded it must lie within and behind the projection of another face as seen from the sun
- (6) calculate f the fraction of area shaded, which is equal to the number of shaded scan points divided by the total number of the face
- (7) calculate the energy received/m^2 of the face, which is given by:

$$900\ (1 - f)\ I \cos(\theta)\ \mathrm{kJ/m^2}$$

where θ is the angle between the sun's direction and the normal to the face, and 900 is the number of seconds in the 15 min sampling interval.
- (8) repeat steps (4)–(6) for each face of interest
- (9) make monthly and yearly summations for each face of interest

The process is speeded up by computing, for each face of interest, a list of the faces which could possibly cause shading, based on the extreme values of x'' and y'' for each face. Only faces in this list are used in the shading test at stage (5).

The accuracy of the process depends on the size of the scanning intervals, and these are parameters which can be given in the control data. Finer scanning intervals imply greater computing time, so these must be carefully chosen to suit the required accuracy.

Figure 4 shows an example of a real house in which three locations, A, B and C, were available for siting solar

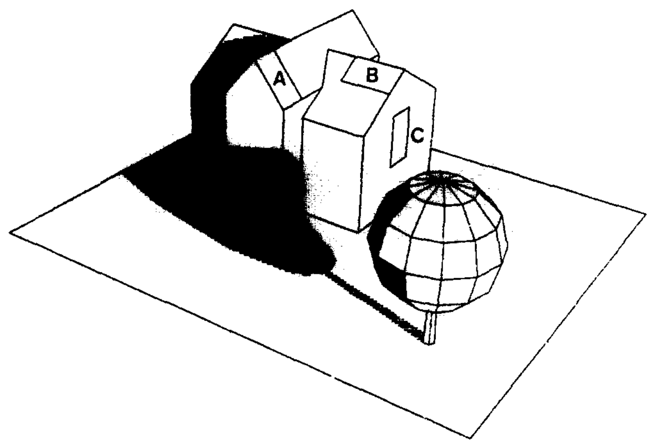

Figure 4. Example of application of the program SHADEN. A, B and C represent possible sites for solar panels

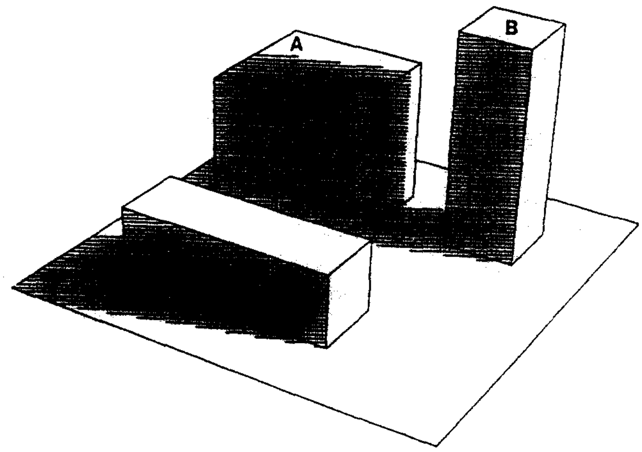

Figure 5. SHADEN was used to calculate the effect of shading by building B on the roof of building A

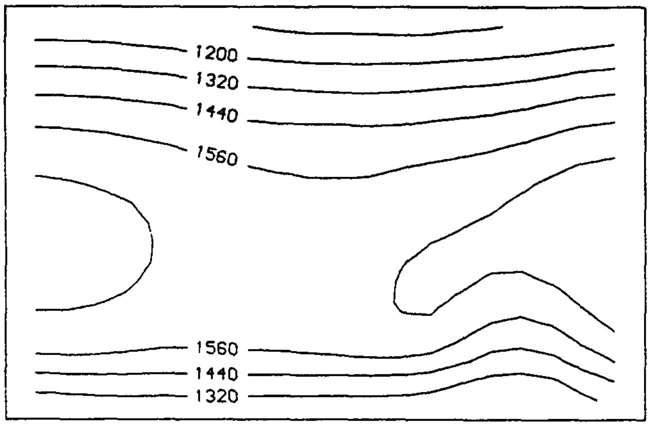

Figure 6. Example output from the program ISOSUN. Contours of direct radiation received on the ground between the building of Figure 3. Contour levels in MJ/m²

panels and it was of interest to calculate the effect of shading by the tree on location C. Using the program SHADEN it was found that, for clear skies, the tree caused a reduction on panel C of 2 per cent in November, 7 per cent in December, and 4 per cent in January. In other months there was no shading of panel C by the tree.

Figure 5 shows a site in which the building B causes shading on the roof of building A. If solar collectors were to be mounted on the roof of building A, it would be of interest to know the reduction in received energy caused by building B. Using the program SHADEN it was found that there was significant shading in the months from September through March with the maximum shading giving a reduction of 11 per cent in the direct solar energy received.

ISOSUN

The program ISOSUN is designed to make a contour plot showing the distribution of direct radiation received on a single face of the building model or on the ground plane. The program makes use of the same file of geometric data as described previously, and the face to be investigated must be specified in the control data. The program calculates the distribution of direct radiation received on the face of interest in any chosen month, or over a specified sequence of months. As with the program SHADEN, calculations are made for four days spaced evenly through the month and the average of the energy received on these four days is scaled by the number of days in the month.

A grid of sampling points is created on the face under investigation and the radiation received is calculated at these points using the same methods as described in the previous section. The fineness of the grid depends on the resolution required and this must, therefore, be specified in the control data. This is done by specifying the number of grid points in the x and y directions across the face. These two numbers determine the size of a 2D array into which the results are integrated. After calculating the radiation received at each of the grid points over the specified period of months, the program applies a 2D smoothing to the results prior to the contour plotting.

As with the program SHADEN, the intensity of direct solar radiation is computed either by assuming clear skies, or by interpolating hourly TRY data.

A limitation of this program is that, for the purposes of contour plotting, the face under inspection must be rectangular. Faces of more complex shape could, however, be studied by dividing them into a number of rectangular sections.

Figure 6 shows the distribution of radiation received on the ground plane of the model in Figure 3, for the months June to August.

CONCLUSIONS

The program package described makes easier the evaluation of the effects of shading, on the direct component of solar radiation, in general 3D building models. The interactive program ICON allows the model to be created quickly, and permits the saving of useful shapes on a catalogue for subsequent use in constructing other models. The provision for holes in model faces is useful for simulating windows. The four batch programs provide graphical display and quantitative analysis of the effects of shading throughout the year.

The programs have a wide variety of possible applications in fields such as:

- building design and layout from both the aesthetic and energy saving points of view
- siting of solar collectors and passive solar components such as windows and trombe walls
- town planning, including legal aspects of shading of light and solar energy by new construction

At present the programs only include the direct component of solar radiation. They, therefore, indicate the worst possible effects of shading for most practical purposes; if diffuse radiation were to be included, the shading would generally have less effect when expressed as a percentage of total radiation received. In most practical situations involving, for example, the location of solar collectors, it is fairly safe to assume that shading is more important for the direct component than for the diffuse, since collectors are mounted in places well exposed to the sun. However, the inclusion of routines to treat the diffuse component would enhance the range of applications of the program package and this is, therefore, being considered.

The computer graphics approach to the problem has proved particularly fruitful as it has provided both visual displays of shading and visual checks on the numerical calculation procedures. The similarity of the shaded areas display problem and the shading calculation problem has allowed similar methods to be used to execute and speed up the graphical and numerical procedures.

The programs are written in Fortran and make limited use of the GINO-F graphics package. They are presently running in a timesharing environment on the Joint Research Centres Amdahl Computer.

ACKNOWLEDGEMENT

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