SOFTWARE FOR SPACE TELESCOPE ASTROMETRY

William H. Jefferys and John Feo
Department of Astronomy, University of Texas,
Austin, TX 78712 USA

ABSTRACT

A general overlapping-plate reduction program, REDUCE, has been written for the reduction of astrometric data from the Edwin P. Hubble Space Telescope. Pains have been taken to make this program powerful and flexible, yet easy to use. This paper describes the main features of the program.

The Space Telescope Science Institute will provide many facilities to assist astronomers in obtaining, calibrating and reducing their data. Among these is an extensive package of software known collectively as SDAS (Science Data Analysis Software). Among the responsibilities of the Astrometry Science Team has been that of defining and writing software for inclusion in SDAS to reduce astrometric data obtained with the Space Telescope's fine guidance sensors.

Since SDAS is a general purpose facility for the use of all astronomers who observe with Space Telescope, the software it contains should be easily used by astronomers who come to the Science Institute. At the same time, as a state-of-the-art instrument, the Hubble Space Telescope will provide data of very high quality which will have to be reduced with the most sophisticated and accurate methods. Combining these two aspects of sophistication and ease of use is a challenging task, and it has been one which the Astrometry Science Team has taken very seriously.

One large program which has been written with this end in mind is called REDUCE. It is a very flexible and powerful overlapping plate reduction program which at the same time has been designed

H. K. Eichhorn and R. J. Leacock (eds.), Astrometric Techniques, 637–641.

to be easy to use. It is described in detail in "REDUCE: User's Manual" (Feo, 1983). In this paper we will give an overall view of this program.

REDUCE comes equipped with a library of standard reduction models (e.g., models with differing parameters for such things as tilt, cubic distortion, higher order distortion terms, etc.) However, since it is not possible to predict in advance all of the uses to which it may be put, very simple and powerful tools are provided so that the user may easily add other models to the available set. Such models need not be linear in the plate parameters; nonlinear models are fully supported. To assist the user in setting up new models, all that is required is for the user to write down the portion of the equation of condition that the specific model entails; thus, a model with four linear plate constants plus tilt terms, with an equation in each of x and y, is specified simply by the following fragment of code:

```
PLATE MODEL TILT2;
PLATE PARAMETERS A, B, C, D, P, Q;
OBSERVATION PARAMETERS X, Y;
BEGIN PLATE MODEL;
PLATE EQUATION =  A*X + B*Y + C + X*(P*X + Q*Y);
PLATE EQUATION = -B*X + A*Y + D + Y*(P*X + Q*Y);
END PLATE MODEL;
```

A star model which includes the parallax of the star is as follows:

```
STAR MODEL PARALLAX;
STAR PARAMETERS MUX, MUY, XI, ETA, PI;
CONSTANT PARAMETERS T;
REAL PX, PY;
BEGIN STAR MODEL;
STAR EQUATION = - PI*PX(T) - XI - MUX*T;
STAR EQUATION = - PI*PY(T) - ETA - MUY*T;
END STAR MODEL;
```

If the above two models were specified for a given plate and star, respectively, then the reductions for the observations of that star on that plate would involve equations of condition that are the sum of the respective plate and star equations. Each plate and star may have its own model. Thus, plates made with different telescopes or Fine Guidance Sensor units can, for example, have different distortion coefficients. Since both an x and a y equation are specified, the use of the above two models would produce a pair of equations of condition for each observation, of the form

```
   A*X + B*Y + C + X*(P*X + Q*Y)
         - PI*PX(T) - XI  - MUX*T = 0;

 - B*X + A*Y + D + Y*(P*X + Q*Y)
         - PI*PY(T) - ETA - MUY*T = 0;
```

A unique feature of REDUCE is the fact that it will analytically take the derivatives in forming the equations of condition for a model. This relieves the user of a possibly onerous task, and is particularly important when nonlinear models are being considered. REDUCE knows how to take derivatives of the standard functions, and can be taught to take derivatives of any arbitrary function. An example of a model using a user-specified derivative is the following:

```
%'&DERIV(COS(#),#)' = '(-SIN(#1)*&DERIV(#1,#2))'
STAR MODEL UNSEEN_COMPANION;
STAR PARAMETERS XCAT, MU;
STAR PARAMETERS LAMBDA, OMEGA, PHI;
CONSTANT PARAMETERS T;
BEGIN STAR MODEL;
STAR EQUATION = - XCAT - MU*T - LAMBDA*COS*OMEGA*T+PHI);
END STAR MODEL;
```

REDUCE takes the specified models and writes a special-purpose program which can solve overlapping plate problems involving any of the models. This program can use different models for different plates and/or stars. The user can easily specify which plates and stars are to be reduced with which model, and can easily change this decision, as well as saving the exact reduction method used on an "environment" file for later reference. In addition, the user may specify that particular plates, stars or observations are not to be included in the reduction. The "environment" file can be tuned and experimented with, and then called up for the reduction of other data at a later time. Finally, if observations and even entire plates or stars are missing from the observation file, REDUCE reconfigures itself accordingly.

The user can specify arbitrary constraints which the plate and star parameters must satisfy. The constraints can be used for a variety of purposes, such as defining the proper motion reference frame, removing singularities from the equations of condition, or enforcing geometrical conditions that are known to be satisfied. Constraints may be applied to individual stars or plates, and may also be applied to groups of stars or plates, at the direction of the user. For example, the following constraint model sets the proper motion of a star to zero:

```
STAR CONSTRAINT SETXMU;
STAR PARAMETERS XMU;
BEGIN STAR CONSTRAINT;
STAR CONSTRAINT EQUATION = XMU;
END CONSTRAINT MODEL;
```

If it were applied to a single object, such as a quasar, this constraint would define its proper motion to be zero and thus implicitly define the absolute proper motions of the other stars in the solution. On the other hand, if applied to all of the reference stars on the plate at once, it would be interpreted by REDUCE to mean that the mean proper motion of the reference stars is zero, thus defining the proper motion system of the reduction. A constraint in this form would be used as one of those required to make the reduction nonsingular. In addition, global parameters whose values are the same for every plate or star are permitted. An example of such a parameter might be a cubic distortion coefficient or the parallax of the target star.

The overlapping plate algorithm used is described by Jefferys (1979), and uses the least squares algorithm described by Jefferys (1980, 1981). At the present time the only method of solution is by normal equations, but we plan to provide an alternative method of solution using orthogonal transformations applied directly to the equations of condition. The program is fully menu driven so that the novice user can easily learn the system. At each menu level, online help is provided in case the purpose or syntax of one of the commands is not clear. We hope that these features will make this program a useful and easily applied tool.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the many contacts and discussions we have had with our colleagues on the Space Telescope Astrometry Team, without which this work could not have been carried out. The support of the National Aeronautics and Space Administration, under NASA contract NAS8-32906, is gratefully acknowledged.

REFERENCES

Feo, John: 1983, "REDUCE: User's Manual", Astronomy Department, The University of Texas at Austin.

Jefferys, William H.: 1979, Astron. J. 84, pp. 1775-1777.

Jefferys, William H.: 1980, Astron. J. 85, pp. 177-181.

Jefferys, William H.: 1981, Astron. J. 86, pp. 149-155.

Discussion:

MURRAY: Is there any practical limit to the number of condition equations you can handle simultaneously, say to the number of stars and the number of plates?

JEFFERYS: The current versions run on a VAX with 4.3 gigabyte address space. There is no intrinsic limitation on how big a system can be accomodated; full use has been made of the sparseness of the coefficient matrix in reducing the maximum order of system that has to be handled. The only limit is therefore a practical one having to do with how long you are willing to wait for an answer.

de VEGT: How can the standard error of the unknowns be computed if orthogonal transfromation are used for solving the normal equation?

JEFFERYS: To compute components of the convariance matrix of the parameters, two methods are available: (1) Individual components can be computed without inversion of the normal equations. (2) The normal equation matrix can be inverted directly in a separate step, which preserves the greater accuracy of the orthogonal transformation method for the parameters.

HARRINGTON: In the actual measurement of ordinates in the FGS, are the lengths of the arms defining the angles constant?

JEFFERYS: The lengths of the two arms are set by the angles of the reflecting surfaces in the star selector servos. When the star selector servos rotate about their centers, the line of right to the star traces out a cone about its center. These lengths are set by the hardware and are constants.

THORNBURG: This is clearly a very capable and flexible piece of software. Will it be available to non-ST users for "general" astrometric use?

JEFFERYS: Yes, we always had in mind that this system be general enough for use in groundbased astrometry as well as for Space Telescope astrometry. Currently the program runs on the CDC Cyber (in an early version) and on the VAX/UNIX, and soon will run on the VAX/UMS system at the Space Telescope Science Institute. Any who are interested in seeing the user's manual or in testing a version of the program should contact the author.

EICHHORN: Would you state for the record why you are switching from normal equations to Householder's transformations?

JEFFERYS: The orthogonal transformation method has the advantages of greater numerical stability and greater accuracy for a given word lenth, at the price of having to execute twice as many instructions. At present we believe we know how to use this technique and take advantage of the sparse nature of the coefficient matrix, but have not had a chance to test this because of having to complete the basic version using normal equations.