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COMPUTER CONTROL OF THE 100 M TELESCOPE

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The development of a computer program for the control of a radio telescope may be an unending task because, on each new level of performance, new wishes will be raised by the observers concerning additional drive procedures, on-line data processing routines, communication means, etc. These wishes are the natural consequence of progress in radioastronomical research, in receiver technology, and also of changes in the composition of the staff of scientists using the instrument. It would be difficult, if not impossible, to anticipate these wishes and to install the corresponding software from the beginning.

However, there are some program features which are dictated by: the telescope hardware; the necessity to store all relevant observational information for later retrieval; and the principles of fundamental astronomy. These features can be foreseen and clearly defined from the beginning, incorporated in the first version of the control program, and left unchanged later on. In the case of the first version of the 100 m telescope control program, a rather high priority was given to a satisfactory solution of the problems connected with these features, whereas, for instance, little priority was given to the demands of the observers for on-line data reduction. It is strongly felt that it is this philosophy that has allowed very efficient astronomical use of the telescope since the summer of 1972, when it came under computer control. The rather high pointing accuracy of the telescope (absolute rms pointing errors are of the order of 7″) is certainly due to three different factors: the excellent quality of the telescope and its drive system, the efficiency of the servo- and monitor part of the control program, and the way in which the principles of fundamental astronomy have been observed in the program.

The 100 m telescope itself has been described elsewhere [1]. Also the overall picture of the astronomical concept [2], details of the digital servo- and monitor-program [3], and the essential features of the special command language have been published [4]. We will concentrate mainly on those features of the control program which are not specifically related to properties of the 100 m telescope and might therefore be interesting for other computer groups in radioastronomy having the same problem, namely to develop a highly flexible and precise computer control system for a radio telescope.

The starting point for the program philosophy is clearly determined by the angular resolution of the encoders which is 2″ for both axes. A precision of about 1″ can be achieved by averaging over consecutive readouts. The astronomical pointing of the telescope is of course influenced by instrumental errors, refraction, errors in the assumed geographic position, and by a possible clock error. All of these effects can be accounted for in a "pointing program" [5] whose analytic form and constants must be determined by observations of point sources with known positions. Let us assume that such a program exists and would allow for utilization of the full accuracy of the encoders. Then, the encoder read-outs could be transformed into azimuths and elevations that coincide with true astronomical azimuths and elevations within 1″. These can be converted into celestial coordinates and then compared with catalog positions if one includes the effects of general precession, nutation and aberration in the comparison. On the other hand, if one ignored nutation and aberration, time- and position-dependent terms would appear in the pointing theory which would make the understanding of the instrumental errors difficult below 20″–30″. Therefore, one important feature in the control program for the 100 m telescope is that all positional calculations have an accuracy of 1″ and that the definitions of fundamental astronomy concerning mean and apparent positions are carefully observed to the same accuracy. It is inconvenient and dangerous for an on-line program to depend on the input of external ephemeris data such as Besselian Day Numbers. Hence, we generate all astronomical time-dependent effects internally. This is, of course, only possible if, in the control program, precise information about the time and the date is available. The computer is interrupted in a 10 ms cycle by a rubidium clock. The clock drives two counters, one for Central European Time, the other one for the number of days (local day counter) which have elapsed since a certain, arbitrarily chosen, fixed epoch. The content of the counters is read by the computer. A special time program runs after each clock interrupt with high priority, checks for consistency of the received time information (and stops the observations if an inconsistency has been found!) and computes the Julian Date and the local mean sidereal time.

Another important area is the choice of coordinate systems suitable for observations. Here one has to distinguish between coordinate systems which are customarily used in astronomy to define positions of celestial objects, and coordinate systems which may be given by the grid of measured points required for the analysis of a particular radio source. A system of the first kind could be called a "basic" system, B, a system of the second kind a "descriptive" system, D. Typical examples of a B–system are mean α, δ (1950.0) or galactic coordinates l^{II}, b^{II}. Special examples for D–systems would be: a system with the origin in the center of a nebula and the equator going along the major axis; or a system with its pole centered in a source and a zero-meridian defined by a certain position angle within the basic system. In the first version of the 100 m telescope control program, the observer can select galactic, equatorial or ecliptic coordinates as a basic system; equatorial and ecliptic coordinates can be defined as either apparent coordinates, referred to the true equinox of date, or mean coordinates, referred to any mean equinox. As far as descriptive coordinates are concerned, he has the choice of letting them be identical with the basic coordinates, or of defining the transformation matrix between B and D by three angles (the basic coordinates of the origin or the pole of D, and the angle which defines the direction of the equator or the zero-meridian of D). A B– and a D–system are connected by a time-independent orthogonal coordinate transformation, represented by a matrix that must be calculated once for a single observational task. Depending on the type of B–system selected by the observer, this matrix may have to be multiplied by other matrices which are either given in the form of constants, like the matrix between galactic coordinates and α, δ (1950.0), or in the form of time-varying coefficients like the general precession matrix. It is then easily possible to calculate at the beginning of each new observation one matrix that directly transforms any pair of descriptive coordinates into mean α, δ for the mean equinox of the epoch of observations. The conversion of these mean coordinates into apparent coordinates and then into astronomical azimuth and elevation is a straightforward task.

This definition of coordinate systems has one particular advantage: it allows logical separation of routine astronomical calculations (i.e. the transition from descriptive to telescope coordinates) from scanning and mapping procedures, because the latter need to be defined only with regard to the descriptive system i.e. with regard to any polar coordinate system. Therefore, scanning and mapping procedures have nothing at all to do with astronomical coordinates, with precession or aberration, or with the many other features of the telescope control program. The control program must simply contain one entry point for a routine which might be called "DRIVE" (see [2], figure 4, p. 106). If we denote the descriptive coordinates by λ (longitude) and β (latitude), DRIVE calculates for each telescope cycle a pair $\lambda(t)$, $\beta(t)$, and these then pass automatically to routine astronomical procedures which generate a pair of telescope coordinates.

Many different algorithms are possible for the DRIVE routine, and it is easy to replace one version by another one. For the first version of the 100 m telescope control program, we selected an algorithm which allows: scans parallel to either one of the two descriptive coordinates with a given scan rate; repetition of a scan any number of times; productions of contour maps consisting of any number of equidistant scans; and symmetric cross scans. The starting position of a scan, a contour map, or a cross scan is given by a fixed reference position in the λ, β–system, and it can in addition be changed by offsets in both coordinates. If observations are made near the origin of the descriptive system, rectangular maps will be obtained; if they are made near the pole, a polar map will be obtained (scans along circles around or along diameters through the pole).

Each such algorithm will require some numerical and/or logical parameters which must be fed into the computer by the observer. This brings us then to the next problem, namely: how can the observer communicate with the control program? A large variety of input terminals is possible nowadays, like teletypes, card readers, thumbwheels etc. For the first version of the 100–m–telescope program, we have selected a teletype as the main input terminal, because it can be programmed in such a manner that it becomes a very flexible and reliable device. A special command language was developed, consisting of one character describing the function of the command, followed by three characters defining the name of the variable to which the command should be applied. The observer types these four characters; if the program considers this combination to be legal, it prints a colon and waits for input of numerical and/or logical information, if necessary, otherwise it ignores it, skips the line and waits for a correct command. Most numerical input will consist of angles (coordinates, offsets, length of a scan, etc.) and angular rates. One of the advantages of a teletype is that one is completely free in selection of angular units and formats–this is purely a matter of programming effort and imagination. In our case, an angle may be represented by one, two or three subfields, separated by blanks. One alphabetic character after the last subfield determines the units, and the values of each subfield may be given in either the *F*– or the *I*–Format of the Fortran language. In this manner, one reaches a maximum of flexibility with a minimum of information that has to be typed. The existence of alphabetic and special characters on the key board doesn't cause confusion because the program can easily be made so that it accepts only numerical digits, blanks or periods, and ignores erroneous input of other characters.

The command language has been described in some detail elsewhere [4], and will not be repeated here. However, one problem associated with this type of communication deserves attention, namely, that it takes some time to input all the instructions that the DRIVE-program needs to execute an observation, and one certainly does not want to waste telescope time while this is done. We have solved this problem in the following manner. The DRIVE-program takes all numerical and logical information from an "active" option array in core memory. This array is not accessible by the observer. The observer inputs his options into a "passive" option array. He is completely free to "work" on this passive array while the telescope executes the various tasks that correspond to the present content of the active array, i.e. to the previous wishes of this or of any other observer. When the new observer has typed and checked all his options, and when the present observing program is finished, the telescope operator pushes a button and causes the transfer of options from the passive into the active array. The telescope doesn't execute the new options immediately. However, the operator can now check the digital displays on the control panel, which show all coordinates, angular velocities, etc. which are commanded by the new options, among them–most important!–the new starting azimuth and elevation values. When the operator is convinced that the new options can be executed by the telescope, he pushes another button, and the new observing program starts.

For the next phases of program development, the incorporation of a card reader and a character display with keyboard is planned. We also feel that it would be desirable to permit input of some fixed-format standard options via a panel with thumbwheels and selector switches. Availability of all these possibilities is advantageous, not only in order to satisfy the different tastes of the various observers, but also to minimize disruptions due to hardware malfunctions. The philosophy of the "passive" and "active" option arrays will also be used in conjunction with terminals other than the teletype. We may even expand this philosophy by defining a number of passive arrays in order to allow for quick automatic (or manually controlled) switching between completely or partially different observing procedures.

The instant at which the telescope operator pushes the start button, defines the epoch, T_o. This epoch plays an important role for that part of the control program which solves the problems of fundamental astronomy. Immediately after the instant T_o, a special program does all preparations which are necessary in order to optimize the CPU–efficiency of the chain of programs which later have to be executed once every telescope cycle. For instance, it calculates the matrix from descriptive coordinates into α_o, δ_o the mean equatorial coordinates referred to the mean equinox of the epoch T_o. (This matrix will be, in general, the product of several matrices, among them the precession matrix between the equinox of the basic system and the equinox T_o). It also calculates all fundamental quantities which are needed to convert the mean coordinates α_o, δ_o into apparent coordinates α, δ with a precision of 1″. One then obtains, with little additional effort, the quantities which are needed to compute radial velocity corrections. Some of these quantities change so slowly with time that they may be considered constant for one or more days. Others change more rapidly and one must also calculate the first time derivations at T_o for later use in a Taylor expansion. Basic quantities which are computed for the instant T_o are: L, the mean geometric longitude of the sun; Γ, the mean longitude of the sun's perigee; g, the mean anomaly of the sun; Ω, the mean longitude of the moon's ascending node; ε, the obliquity of the ecliptic, and e, the eccentricity of the earth's orbit. The definitions of these quantities given on p. 98 and p. 107 of the Explanatory Supplement [6] have been used. From these basic quantities, nutation in longitude ($\Delta\psi$) and in obliquity ($\Delta\varepsilon$) can be computed; we use only the 3 largest terms in $\Delta\psi$ and the two largest terms in $\Delta\varepsilon$ ([6], p. 44–45). The true geometrical longitude of the sun, Θ, follows from the equation $\Theta = L + E + \Delta\psi$ (see, for instance, [7], p. 26), where E stands for the "equation of the center", and is sufficiently represented by the two largest terms in eccentricity. The original Besselian Day Number method has been slightly modified, firstly, because we are processing source positions rigorously to the instant T_o (instead of the beginning of the nearest Besselian year) and secondly, because we wish to pre-calculate as much as possible for the instant T_o and leave only a minimum of calculation to be executed during the telescope cycle. Our modified Besselian Day Numbers are therefore given by the following equations:

$$\begin{aligned} A_1 &= \Delta\psi \sin\varepsilon & D_1 &= -A_3 \\ A_2 &= -\Delta\varepsilon & D_2 &= A_4 \\ A_3 &= -k\cos\Theta\cos\varepsilon & D_3 &= A_1 \\ A_4 &= -k\sin\Theta & D_4 &= -A_2 \\ A_5 &= \Delta\psi\cos\varepsilon & D_5 &= -k\cos\Theta\sin\varepsilon \end{aligned}$$

where k is the constant of aberration. The constant A_5 is the "equation of the equinoxes" and has to be used for the conversion of mean into apparent sidereal time.

The "star constants" which must be available at each telescope cycle are

$$\begin{aligned} c_1 &= \sin\alpha\sin\delta & c_3 &= \cos\alpha \\ c_2 &= \cos\alpha\sin\delta & c_4 &= \sin\alpha \\ & & c_5 &= \cos\delta \end{aligned}$$

c_3–c_5 are available anyway as result of coordinate transformations, and only c_1 and c_2 have to be calculated in addition. The reduction from the mean to the apparent place can then be written as follows:

$$\Delta\alpha\cos\delta = \sum_{i=1}^{5} c_i A_i \qquad \Delta\delta = \sum_{i=1}^{5} c_i D_i$$

This method is good enough to guarantee a positional accuracy of 1″ even if T_o is kept constant for one day or more. However, since every change in the input options leads to a new definition of T_o, all the constants are updated often and no accuracy problem arises.

For radial velocity corrections, one has to calculate–besides the trivial diurnal effect–the heliocentric velocity and acceleration components of the earth-moon barycenter for the instant T_o:

$$\begin{aligned} \dot{X}_o &= V(\sin\Theta + e\sin\Gamma), & \ddot{X}_o &= V\cos\Theta\,\tfrac{d\Theta}{dt}, \\ \dot{Y}_o &= -V(\cos\Theta + e\cos\Gamma)\cos\varepsilon, & \ddot{Y}_o &= V\sin\Theta\cos\varepsilon\,\tfrac{d\Theta}{dt}, \\ \dot{Z}_o &= -V(\cos\Theta + e\cos\Gamma)\sin\varepsilon, & \ddot{Z}_o &= V\sin\Theta\sin\varepsilon\,\tfrac{d\Theta}{dt}, \end{aligned}$$

where V is the mean orbital velocity of the earth (29.79 $\mathrm{km\,s^{-1}}$) and where $\frac{d\Theta}{dt}$ is easily obtained from the expression for Θ. During the telescope cycle, the instantaneous velocity components are obtained from the first two terms of the Taylor expansion. In order to obtain the LSR–correction, one has to calculate the 3 components of the solar motion for the instant T_o. The standard solar motion, referred to the mean equinox 1950.0, is stored in memory and is precessed to the epoch T_o. If an observer wants to use a solar motion different from the standard motion, it would be easy to change the corresponding constants.

In this manner, both heliocentric and LSR corrections are computed on-line. At the present time, they can be displayed at the control console. Later, they will be used to control, automatically, the frequency setting for line work or to control apparent pulsar periods.

The absolute accuracy of these radial velocity calculations is not better than 10–20 $\mathrm{m\,s^{-1}}$, because the following effects are not taken into account: the motion of the earth around the earth-moon barycenter, the motion of the sun around the planetary barycenter, and the direct periodic perturbations due to the planets. We are presently working together with G. Hunt (Max-Planck-Institut für Radioastronomie) on the possibility of approximating the periodic perturbations by evaluating the most significant terms in Newcomb's theory of the sun. We hope that in a later version of the program it will be possible to calculate these perturbations and the two other effects with an absolute accuracy of at least 0.5 $\mathrm{m\,s^{-1}}$.

Θ and $\frac{d\Theta}{dt}$ have to be computed for the positional and velocity requirements and so are already available; we use these functions to compute the position and velocity of the sun at the instant T_o and then, for each telescope cycle, to compute approximate values of $\alpha_\odot$, $\delta_\odot$, using the first two terms of a Taylor expansion. Presently, the sun's coordinates (which might have errors up to 20 or 30 arcsec) are used in the on-line program to display the angular distance of the commanded telescope position from the sun, so that pointing the telescope directly at the sun can be easily anticipated and avoided, if necessary. In a later development, this information could also be used, for instance, to produce some warning signal if the sun is located in a sidelobe of the antenna beam.

As far as the computational methods we are using in the control program are concerned, some remarks should be made with regard to general coordinate transformations. A complete transformation between any two coordinate systems concerns always 5 quantities: two spherical coordinates, two angular velocity components, and an arbitrary position angle. Let us call these quantities L, B, $\dot{L}$, $\dot{B}$, P in the given system and $l, b, \dot{l}, \dot{b}, p$ in the wanted system. The transformation matrix $((t_{ik}))$, is assumed to be known. The transformation of the coordinates is calculated from

$$\begin{pmatrix} \cos b \cos l \\ \cos b \sin l \\ \sin b \end{pmatrix} = ((t_{ik})) \cdot \begin{pmatrix} \cos B \cos L \\ \cos B \sin L \\ \sin B \end{pmatrix}$$

To transform the velocity components and the position angle, one has to determine explicitely the parallactic angle, ω, which belongs to the transformation. For this, one can use one of the following sets of equations:

$$\begin{aligned}
\cos B \cos \omega &= -\sin b \quad (t_{13} \cos l + t_{23} \sin l) + t_{33} \cos b \\
\cos B \sin \omega &= \qquad t_{13} \sin l - t_{23} \cos l \\
\cos b \cos \omega &= -\sin B \quad (t_{31} \cos L + t_{32} \sin L) + t_{33} \cos B \\
\cos b \sin \omega &= \qquad -t_{31} \sin L + t_{32} \cos L
\end{aligned}$$

Which one set is more suitable depends on the magnitude of $\cos B$ and $\cos b$.

The velocity transformation is given by the equations

$$\begin{aligned}
\dot{l} \cos b &= -\dot{B} \sin \omega + \dot{L} \cos B \cos \omega \\
\dot{b} &= \dot{B} \cos \omega + \dot{L} \cos B \sin \omega
\end{aligned}$$

All the above equations are valid as long as both systems are either right- or left-handed. However, in the case of the position angle, if one wants to keep a unique definition on the sky which is independent from the rotation sense of the coordinate systems, one has to use the equation

$$p = P \pm \omega$$

In our case, we have defined positions angles such that the upper sign holds for left-handed systems (for example: conversion of hour angle-declination into azimuth-elevation), and the lower sign for right-handed system (for example: galactic into equatorial coordinates).

The telescope cycle time is 50 ms, and is determined by the telescope hardware. The logical sequence of tasks that must be run in a telescope cycle is the following: the DRIVE-program calculates values of λ, β. These, and the values of the scan rates and of the position angle which were specified by the observer are transformed into the mean equatorial system referring to T_o. Next, mean sidereal time is converted into apparent sidereal time, and the reduction from mean to apparent α, δ is carried out. At this point, also, the calculation of radial velocity corrections and of the sun's coordinates is performed. The differential effects that nutation and aberration produce in the angular velocities and in the position angle can be neglected, i.e. their mean values are assumed to be identical with their apparent values. A second transformation converts them into the horizontal system, calculating the instantaneous values of the azimuth and elevation and their rates and the feed angle.

The observer has input options which produce, at this point, additional offsets in azimuth and elevation. He also can apply scanning-, mapping- and cross-scanning procedures in azimuth and elevation, provided that he has not already done this in the λ, β-system. In other words, scanning operations are possible either in λ, β or in azimuth-elevation. This latter possibility is mostly used for telescope calibration measurements; in this case λ and β are kept constant and specify the position of the calibration source which is tracked, while simultaneously scans in azimuth or elevation are superimposed.

To the computed instantaneous values of azimuth and elevation are added pointing corrections which are calculated by the special analytical pointing program mentioned at the beginning. This program also computes and applies the additional offsets which correct for the computer controlled focus displacements of the homology telescope. The final results of all these procedures are then used in the servo program to minimize the difference between commanded and indicated telescope coordinates.

This effectively summarizes the tasks of the control program which are prescribed by the definitions and methods of fundamental astronomy and apply to any telescope of a similar precision and quality. There are many more tasks which have to be executed, like servicing the operator's control panel, sending messages to the operator concerning the instantaneous conditions of the telescope drive system, etc. However, they depend on our local hardware conditions and are not of general interest.

Another important aspect of a control program is the interaction between the astronomical drive program, the servo program, the acquisition of receiver and associated data and their storage onto magnetic tape. In the 100 m telescope control program, the receiver output is read into the computer continuously. A very basic on-line data reduction informs the observer of the output of the receiver. The data are stored for further reduction only if the telescope is pointed to the area specified by the observer. In the case of a scanning procedure the observer inputs starting point, length and velocity for the scan. A further parameter is the basic integration time for a single data point. If the time specified by length and velocity is not a multiple of the basic integration time, the measurement will be continued until the last integration cycle is completed. This is an example of a situation in which the data acquisition program influences the drive program. There is, likewise, an interaction between the drive program and the program that records data on magnetic tape: the data are collected in a buffer until a specified block size is reached. The data block is then written onto tape and the transfer is checked by rereading the tape and comparing with the data in the buffer. If the comparison fails, the transfer is repeated and rechecked. Meanwhile, the data acquisition is continued into a second buffer. If the second buffer overflows before the first one is successfully transferred, the observing program is interrupted. It can only proceed after the data are written properly onto tape. In this way the observer can be certain that all his data on tape is formally correct and complete.

Finally, one should pay attention to the importance of two more demands which might appear to exclude each other: the tape should have complete information, but should be as short as possible. We try to satify these demands in the following way. In all types of experiments, there will be always a smallest "data cycle" which is repeated. Each data cycle may produce one or more computer words. For example, the four-phase digital continuum back-end inputs 4 computer words once every 64 ms. We store them all on tape while the telescope is scanning according to the input of the observer. For complete information one needs a few additional numbers for each data point. We call them data associated parameters. They contain the time, the indicated telescope positions, and the position residuals which are left by the servo loop. Further information, which is constant throughout an entire scan, is also needed. This is contained in a header which specifies all the input options of the observer, as stored in the active option array. The header must in addition contain other important things like the epoch T_o. Given all of this information, the observer is able to reconstruct in an off-line program precisely what he intended to do during observation, and what the telescope has actually done. To make such a tape philosophy highly flexible, one can go one step further and let the header start with a few words which have information about the number of words in the header, in a data-point, and in a set of data associated parameters. It is then possible to have a number of different experiments on the same tape, having different number of words per data point, different header length, and so on. A general off-line tape reading program can be constructed which automatically detects these differences, using a standard routine for "header interpretation", and then correspondingly branches to the specific task that is appropriate for a specific experiment. For the 100 m telescope, we have found this concept helpful as a first approach to a generalized data processing system.

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