The FORTH Program for Spectral Line Observing

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Abstract—**The 11-m telescope of the National Radio Astronomy Observatory (NRAO) on Kitt Peak is extensively used for spectral-line observing at millimeter wavelengths. The computers that control the telescope and receiver have been programmed in FORTH. This language provides an extensive vocabulary for the astronomer to use to control his observation and reduce his data. Here we summarize the capabilities provided by the most common words of this vocabulary—capabilities ranging from telescope tracking patterns to fitting line profiles. It is noteworthy that the number of words required for sophisticated observing is large and growing.**

Introduction

THE STUDY of spectral lines from interstellar molecules is presently an important and exciting branch of radio astronomy. Lines at millimeter wavelengths are being observed by astronomers from many organizations at the National Radio Astronomy Observatory's 11-m telescope on Kitt Peak, Arizona. Although several receivers are used, all share the same system for data collection, storage, and reduction. The equipment used is diagrammed in Fig. 1.

When the system was designed in 1970, it was recognized that the ability to calibrate and analyze data at the telescope would greatly enhance observing efficiency. In fact, the on-line program SPECTRA provides such extensive data-reduction capabilities that many users find further off-line processing unnecessary. Although the spectra are recorded on magnetic tape, primary output thus consists of 8½- by 11-in prints of the screen of the Tektronix 4002 graphic terminal. The computer will label the picture and the user can annotate it further so as to provide documented spectra in the precise format desired. Figs. 2–4 are direct reproductions of the system output.

The computer is programmed in FORTH, a software system/language designed specifically for interactive applications [1]. It provides a multiprogrammed environment with four tasks running concurrently: telescope tracking, data collection, a printing terminal for the telescope operator, and a graphic terminal for the astronomer. In this paper we will describe how some of the unique features of FORTH make it possible for users to interact with equipment and data in a flexible and sophisticated way. More detailed information is provided in an NRAO internal report [2].

Especially with a program as complex as SPECTRA, user-oriented documentation is essential. Ours is organized to increase gradually the vocabulary known to the astronomer, and thus increase the precision with which he can direct the computer. The first stage is a two-page summary of the minimum vocabulary needed to observe. Once the confusion of beginning has abated, he can read off and try out words concerned with display, data-reduction, and extended observing.

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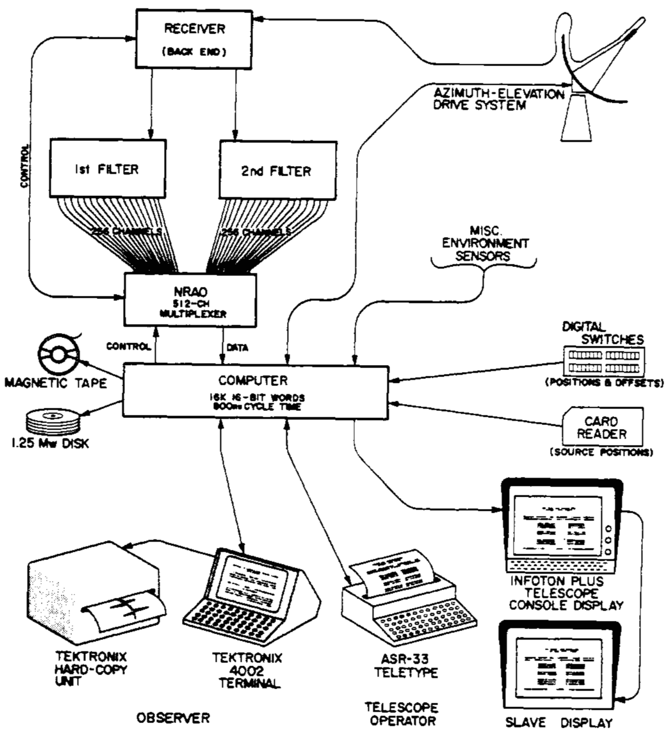

Fig. 1. NRAO's 11-m telescope control and millimeter-spectrum observing system.

With the multiprogramming available, he can test words, display data, define abbreviations—all without interfering with observations or tracking.

User Interface

A major role of the computer is to operate an interface between user and equipment. Most of our observers are visitors who observe only a few times a year, which requires that the interface be easy to learn, to use, and to remember. A custom control panel is one possibility, and indeed is used for telescope control. But this tends to be awkward and inflexible, and altogether unsuited for an elaborate data-processing task.

Therefore, we use the Tektronix keyboard as the main input from the astronomer. He is provided with a very large vocabulary composed mostly of English words (CALIBRATE, RANGE) and simple abbreviations (SEC for seconds), and is expected to type words and phrases to direct the computer. FORTH is tolerant of misspellings, and permits backspacing and canceling of messages as an aid to the typist.

SPECTRA employs words that are spelled out in full. In general, the brevity of abbreviations is offset by the difficulty of remembering the abbreviation as well as the word. However, the ability to abbreviate by constructing definitions is an integral part of FORTH. In fact, most of SPECTRA is programmed using high-level definitions and a user is encouraged to add those that suit his taste. For example, he may decide to repeat sequences of 4 on–off measurements. To start a sequence he would type

```
4 ON-OFF
```

If he wishes, he can define the word G by typing

```
: G 4 ON-OFF ;
```

and thereafter typing G will start the sequence. The syntax for an abbreviation is simple: the word being defined is preceded by a colon and followed by its definition, which ends with a semicolon.

Telescope Control

The 11-m telescope has an azimuth-elevation mount, which means that the computer must convert equatorial to local coordinates. The telescope is controlled from a console that includes switches, a keyboard, and a card reader. The card reader provides text exactly like the keyboard for FORTH to interpret. A vocabulary is defined that gives the observer exceptional control over where the telescope points and how it moves.

One of the multiprogrammed tasks is to continually move the telescope to a specified position. Pointing corrections are determined periodically and automatically applied to provide ±5″ rms tracking accuracy. Each receiver produces a peculiar beam offset which is determined when the receiver is mounted and thereafter compensated. The tracking error is displayed and delays data collection if it exceeds a specified limit (10″). This prevents wind gusts from spoiling a long observation and automatically starts (or continues) the observation when the telescope reaches position.

The simplest pointing command is to type (or punch)

```
20:38:02.2 42:13:32. CURRENT DR21
```

which specifies the current RA/DEC of the source DR 21. The telescope will move to its apparent position and track it until further notice. Alternatively,

```
20:37:14.2 42:09:07. 1950 EPOCH DR21
```

specifies the source position in 1950.0 coordinates, to which precession, nutation, and aberration corrections are added. Likewise, galactic coordinates may be specified (if precisely known) as

```
81.6794 0.5391 GALACTIC DR21
```

To follow a planet requires the positions and rates listed in the American Ephemeris. Cards are available for the current year. The words ZENITH and SERVICE move the telescope to fixed positions.

In addition to tracking a fixed or moving source, several more elaborate observing patterns are possible. The word ON-OFF directs the telescope to switch between the source and the nearby blank sky, to cancel systematic and atmospheric effects. The amount of this offset is specified by the observer, and may be chosen for dual-beam receivers so that the two beams alternate on and off the source.

A common type of observation is to map a region of the sky. MAP performs a raster-scan in either equatorial or galactic coordinates about a source position. The grid dimensions and integration time are controlled by the observer. The data are calibrated and formatted in convenient form for display.

In order to accurately locate a point source, the word FIVE will record measurements at five points—north, south, center, east, and west—about the source. The observer may request a least squares Gaussian fit to azimuth and elevation offsets, beamwidths, and peak temperature. This is normally used for continuum measurements, but is useful to determine pointing corrections for the line receivers. Similar patterns can be easily defined to suit special needs.

Atmospheric extinction is measured by EXTINCTION. Eleven samples are taken at six elevations and a function with a linear term for receiver-gain drift and an exponential term for attenuation is fitted. Thereafter data will be corrected for the observed extinction.

These routines are all coded as high-level definitions. Each controls the telescope position as it requires and applies significant processing to the raw data. The result is efficient observing and immediate feedback to the observer about the quality of his data.

Receiver Control

The astronomer can choose from a variety of equipment and techniques. As of fall 1973, spectral-line observing will be done with two filter banks with 256 1-MHz and 256 0.25-MHz channels. These accept a signal from a receiver with interchangeable mixers (some of which belong to visitors) that cover the 2–7-mm band.

Lines whose antenna temperatures are only 1 K are superimposed on perhaps 1000-K system noise, so means must be provided to cancel this background. Signal and reference spectra are alternated at 10 Hz and subtracted by the computer. Reference spectra are provided by changing frequency, switching to a hot load, or moving the beam with a nutating subreflector. In addition the antenna may be moved on and off source, though at only 0.1 Hz. In practice, best results have been obtained by combining antenna switching with frequency switching. This requires the program to integrate 4 512-word arrays and combine them to produce the spectra.

Receivers fall into two categories regarding calibration. Some provide a 400-K single-sideband temperature by switching sky and hot load with a chopper wheel. Others provide 100-K temperature as the computer switches a noise tube on and off. In either case, the spectrum is recorded on tape as calibrated antenna temperatures in each channel. Two formulas are available for computing temperatures. The choice depends partly on the receiver and partly on taste. Three combinations of calibration technique and temperature formula are offered as standard. Typing NRAO or CHOPPER or BTL chooses one. A new combination could be defined in a short time, though not by the average observer.

To begin an observation, the astronomer specifies a source position, usually punched on a card, and the line frequency and source velocity, usually typed. The computer will compute the velocity of the earth and provide (or verify) the local-oscillator setting. The astronomer must tune the receiver, set switches, and type CALIBRATE to perform a calibration and display the result as a system-noise spectrum. Then he resets and types 1 ON-OFF to begin a measurement switched in position and frequency.

Several parameters influence the observation. Their values are displayed by typing STATUS and may be easily changed. For example,

```
30 SEC !
```

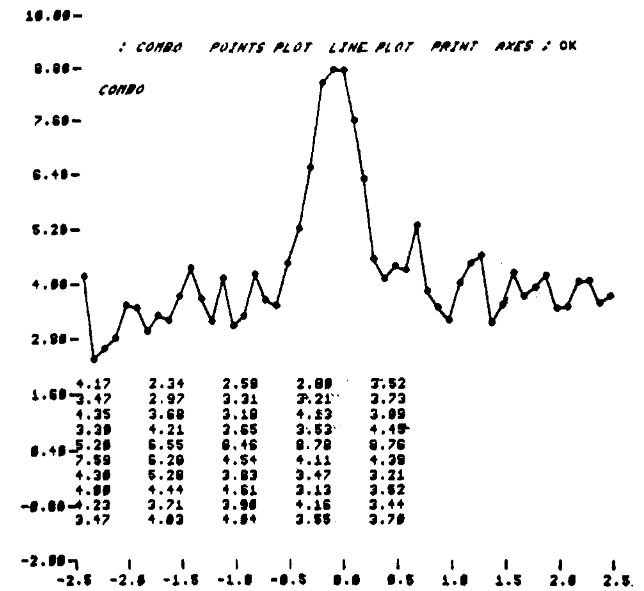

Fig. 2. Output produced by the word COMBO: a spectrum plotted as points and line with vertical axis in Kelvins and horizontal axis in megahertz. The values of the points are also printed.

changes the integration time to 30 s. Important parameters are recorded with the data.

Displays

Of equal importance with specifying an observation is verifying that it has been obtained. A major part of SPECTRA is concerned with displaying the data legibly and accommodating a variety of observer preferences. The user may display the data currently being collected, recall data recorded earlier, or combine spectra recorded separately—either in time or frequency.

Since two spectra are obtained simultaneously, the one of interest is specified by 1ST or 2ND for the 1-MHz or 0.25-MHz filters, respectively. Typing PLOT will redraw the last spectrum if parameters are changed, or if the screen is cluttered (with a storage-tube display spectra are often superimposed). The word BOTH will display both spectra (of differing resolution) on the same horizontal frequency axis. This axis is controlled by 1ST FREQUENCY or 2ND VELOCITY that specify either frequency or velocity scales. Likewise, 0 1000 RANGE sets the vertical temperature range to 0–10.00 K.

Recorded with the data is an estimate of the standard deviation of a channel. This is calculated from the channel bandwidth and integration time. The word BARS displays the data with error bars. These errors are properly propagated by the analysis words discussed below. Alternately the observer may specify POINTS or LINE or HISTOGRAM to select a plotting format. Each observer usually defines a word that produces the plots he likes. For example,

```
: COMBO   POINTS PLOT LINE PLOT PRINT AXES   ;
```

produces the display shown in Fig. 2.

Spectra recorded over several days may be combined by entering their scan numbers in a table. Typing SHOW will recall all the scans with a vertical offset between them. They should have a strong resemblance, even though noise is present, and bad data usually stand out clearly. The word COMBINE will combine these scans into a single spectrum, weight-

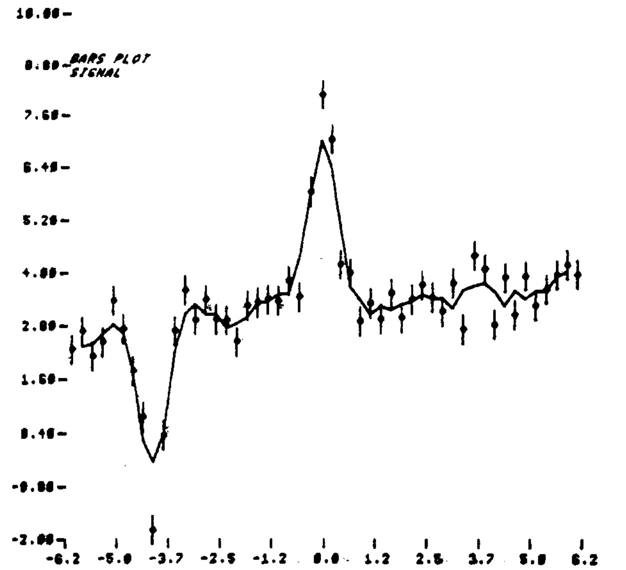

Fig. 3. A spectrum plotted with error bars. The output of SIGNAL is superimposed: points plotted and a smoothed line drawn.

ing as appropriate by integration time and aligning the fre quencies of each. This spectrum is the final datum produce by SPECTRA. It may be labelled, titled, and annotated int a very nearly publishable format (legibility is not up to pub lishing standards).

The last spectrum drawn is stored in a display buffer There are several words that act upon this buffer in an at tempt to extract information from it. SMOOTH will smooth the spectrum and display the result. It convolves the dat with a 7-point function. Typing HANNING or BOXCAR o BAND-LIMIT selects a 3-point triangle, a 3-point rectangle, o a 7-point approximation to sin $(x)/x$. Or the observer ma define a function. Defining the word

```
: SIGNAL   POINTS PLOT LINE SMOOTH AXES   ;
```

will display the data points with a smooth line through them—a pleasing picture as shown by Fig. 3.

However, the most powerful way to extract information i to define a model based either upon prior knowledge or visua pattern recognition. The line-fitting ability of SPECTR provides the clearest example of the value of interaction be tween observer and computer via a powerful language. A spe cial vocabulary permits defining a function and fitting it b least squares to the weighted data stored in the display buffer For example, typing PEAK specifies a single Gaussian with constant baseline.

```
0   100   1000   0   GUESS
```

specifies initial values for position, half-width, amplitude, an baseline. Typing CURVE will draw the function thus specified presumably superimposing it upon data previously displaye If it agrees reasonably well with the data, FIT will perform single least squares differential correction to the parameter and draw the new function. Even a simple Gaussian become a nonlinear function in the presence of a baseline, so the ob server may type AGAIN to perform another iteration until he i satisfied of convergence—or decides to start over. RESUL types the final values of the parameters and their standar deviations, as determined from the data.

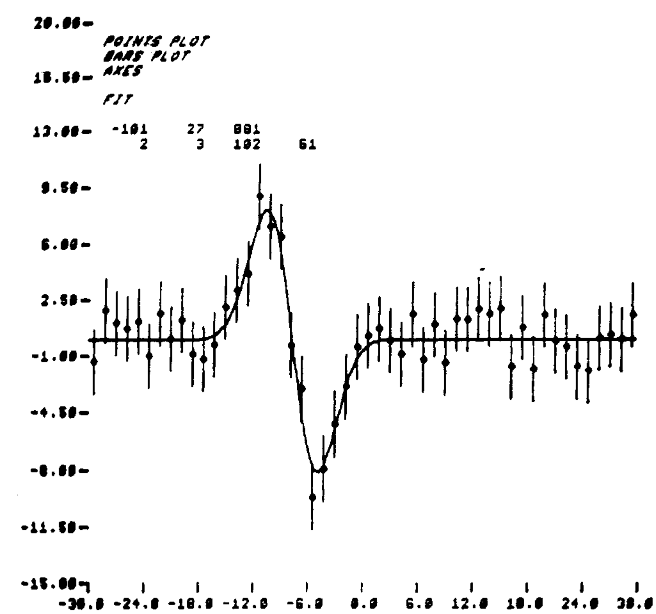

Fig. 4. A spectrum plotted with points and error bars with the final least squares fitted to the difference of Gaussians drawn. The numbers indicate the position, width, and height of the positive peak, with standard deviations underneath. The negative one has the same shape and a fixed offset.

In order to cope with the enormous variety of possible spectra, we have devised basic functions and means of combining them. Multiple lines with Gaussian, saturated Gaussian, or Lorentzian profiles, and constant, linear, quadratic, or sinusoidal baselines may be specified—as well as combinations of lines with fixed separations and amplitude ratios for hyperfine splitting observations. The only limit on the function is a total of 10 parameters. For example, the function above is specified

```
: PEAK  4 PARAMETERS  ASSIGN START GAUSSIAN
        CONSTANT ;
```

An example of a frequency-switched Gaussian (fixed separation, equal amplitudes) is shown in Fig. 4.

FORTH

Of course, any of the features of SPECTRA could have been coded with conventional techniques. But it is unlikely that the entire program could have been realized except in FORTH. There are several reasons.

FORTH is *core efficient*. SPECTRA runs in less than 16K 16-b words, without any overlays, and includes (in addition to the observing vocabulary) the core resident assembler, compiler, and interpreter which makes it possible to define new words. A parameter stack eliminates the need for calling sequences and makes FORTH compilations very compact. At its high level, FORTH is several times more efficient with core than assembler code.

FORTH is *fast*. Externally it is an interpretive language—the words a user types are looked up in a dictionary and executed. But unlike other languages, it *compiles* definitions so that *executing* them does not require repeated dictionary searches. Thus the overhead for high-level definitions is equivalent to a subroutine call—only a few microseconds. This makes it possible to code even central parts of the system such as telescope tracking and data handling as high-level definitions, which greatly increases their flexibility and accessibility.

FORTH is *interactive*. The data reduction available requires interaction between the observer and computer. Since FORTH is *inherently* interactive, no special programming is required to make this possible. Moreover, even aspects of the system where interaction is not normally thought necessary, such as telescope control, benefit. For it is extremely easy to diagnose malfunctioning equipment, or test new equipment, by communicating with it directly from the terminal.

FORTH is *responsive*. FORTH programs are kept in source form on 100 Kbytes of disk (or tape). They may be quickly modified and recompiled (in minutes) without the cost and complexity of separate compiler, assemblers, loaders, and operating system. Thus over the years SPECTRA has been in use, it has been able to incorporate the suggestions made by its users, including many trivial conveniences the sum of which makes it comfortable to use. It can easily adapt to new hardware, reflect changes in receiver use, and make allowances for inoperable equipment.

In addition to these attributes, which are essential to SPECTRA, FORTH's high-level definitions are also computer independent. An increasing number of other observatories are now developing FORTH programs, and a growing library of techniques is available to these users, including many of those described here.

References

[1] C. H. Moore, "FORTH: A new way to program a minicomputer," to be published in *Astron. Astrophys. Suppl. Ser.*, 1973.
[2] E. D. Rather and C. H. Moore, "FORTH programmer's guide," NRAO Computer Division Int. Rep. 11, 1972.