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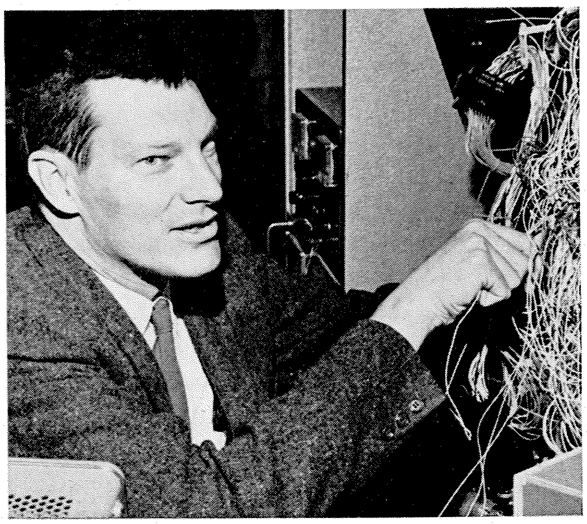
ELECTRONICS AND THE NEW ASTRONOMY

by Edwin W. Dennison

In 1964 a panel concerned with astronomical facilities prepared a report for the National Academy of Sciences covering a ten-year program for ground-based astronomy. This report emphasized the shortage of ground-based optical facilities and projected the increasing inadequacy of observing resources. It also pointed out the urgency of improving the operating effectiveness of the telescopes in existence.

For the past three years the Mount Wilson and Palomar Observatories Astro-Electronics Laboratory has undertaken an electronic instrumentation program to achieve these goals. We began with a summary of some aspects of the relationship between optical ground-based astronomy and space astronomy. These two sources of information about extraterrestrial objects can supplement each other only if the ground-based telescopes are equipped to operate at the most advanced levels of technology. If we turn to space astronomy for data which we are not able to get from ground-based telescopes only because we have failed to develop new techniques, we are in an economically indefensible position and will have subjected our space experiments to a somewhat greater possibility of failure. By testing new techniques on the ground-based telescopes we gain experience from which we can further develop space experiments and hardware.

In June 1964 Ira S. Bowen, at that time director of the Mount Wilson and Palomar Observatories, analyzed the relationship between telescope apertures, exposure times, auxiliary instruments, and the efficiency of any given telescope for meas-



Edwin W. Dennison is a staff member of the Mount Wilson and Palomar Observatories and head of the Observatories Astro-Electronics Laboratory on the Caltech campus. The laboratory came into being in September 1963 in recognition of the need to advance the techniques and equipment used at the observatories and to develop new equipment. Dr. Dennison and his staff design, build, install, and maintain all the electronic equipment used in connection with the Mount Wilson and Palomar telescopes.

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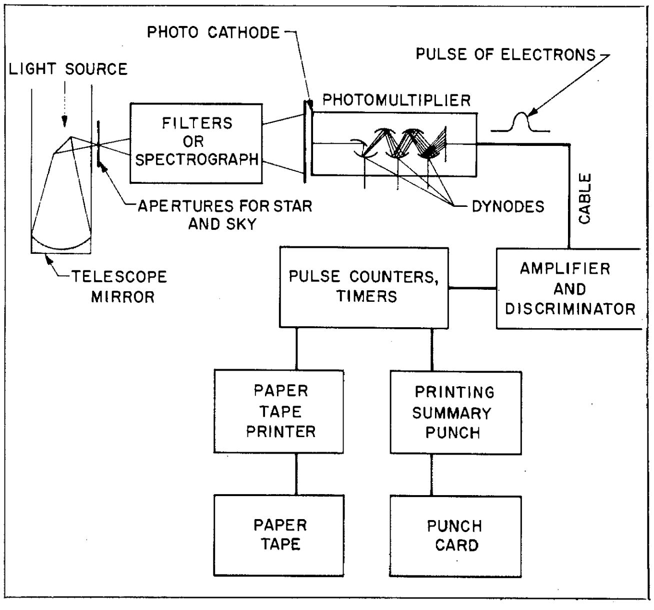
"Electronics and the New Astronomy" has been adapted from a talk given by Dr. Dennison at a conference on The New Astronomy and Its Technology, sponsored by Caltech's Office for Industrial Associates on February 9.

uring faint objects or spectral lines. Although he dealt primarily with the problems of determining the direction that future telescope builders should take in selecting telescope apertures, it is interesting to note that his results state that observing time and telescope light-collecting area are interchangeable. In other words, a telescope with a collecting area twice as large as another can make the same observations with the same degree of accuracy in half the time. This is the primary reason for building large telescopes. However, for any telescope with an aperture larger than about 16 inches, there is very little gain in angular resolution—the ability to distinguish between two points in space. Dr. Bowen concludes that when all factors are considered, a 200-inch aperture is optimum.

An auxiliary instrument that speeds up the operation of a large telescope is equivalent to an increase in the effective aperture. Since the value of the 200-inch telescope is almost $10,000,000, any device that increases operating efficiency by 10 percent can be considered to be worth almost a million dollars. Clearly, these devices are an economical way of increasing the power of large telescopes.

One of the first experimental projects our astro-electronics lab initiated along this line was the modernization of the photon-counting techniques used with the 200-inch telescope.

In a photon-counting system (see diagram below), for every four or five photons that strike the photo cathode, one photoelectron is emitted. This electron is accelerated through a series of dynode amplifiers and is multiplied by nearly a million. These electrons emerge from the photomultiplier as a single electrical pulse, the duration of which is about ten nanoseconds (a nanosecond is a billionth of a second). An amplifier increases the pulse amplitude by about 2,000, and a discriminator rejects low amplitude noise and interference pulses. The pulses are then counted by an electronic counter. From the beginning of this cycle—the single photoelectron to the pulse counter—the over-all amplification is two billion.



Block diagram of a typical pulse-counting photometer and data system used with large telescopes.

New high-speed amplifiers

The original system we built was somewhat primitive and had a time resolution (the ability to distinguish between two pulses) of only one microsecond, or approximately one hundred times longer than the duration of the pulses coming from the photomultiplier. Eventually we were able to get high-speed pulse amplifiers that have a time resolution of about ten nanoseconds. These new pulse amplifiers and discriminators have another great advantage. By virtue of their compactness, they are less subject to interference from TV stations on Mount Wilson and from telescope control relays.

The high-speed systems are not needed for counting photons from most of the extraterrestrial objects astronomers are now studying. Many of these images have pulse counts as low as only 10 to 100 counts per second as compared to counts of up to three billion for very bright stars. However, the high-speed systems are necessary for calibrating the photometers by measuring the brightness of standard stars (up to three million counts per second).

The first data system we built for the 200-inch, which is still in service, uses a reversing counter. This system has two apertures, one covering the star plus a certain amount of sky background, the other, adjacent to it, covering an equivalent amount of sky background only. A mechanical "chopper" switches back and forth between the two apertures at a rate of 15 cycles a second, permitting the light input from each to be recorded alternately. When we are looking at the star-plus-sky background, we can make the counter count in a plus direction; when we are looking at the sky background alone, the counter will count in a negative direction. The accumulated count represents the difference between the two, or the count due to the star alone.

In the improvement of our entire photometer system, the next logical step was to go to a two photomultiplier system. This system has been constructed but has not yet been used. It has two photomultipliers, each looking through one of the two apertures. One looks at the star-plus-sky background; the other looks at the sky background alone. A small mirror, activated by a stepping motor, moves back and forth between the two and reverses the role of the two photomultipliers so that the first photomultiplier looks at the sky background, the second at the star-plus-sky. This addition of the second multiplier immediately doubles our observing capability but requires that we have the two reversing counters to operate the system.

The next degree of sophistication in the advancement of our instruments is a 33-channel spectrophotometer—an instrument still in the design and development stage. It will contain 33 photomultipliers operating simultaneously. The optical part of the device is similar to the single photomultiplier system, with two apertures and a chopper. Because of the large size of the system and its cost, it is more economical to use 66 unidirectional counters rather than 33 reversing counters. The system records all the data, and the computers take the difference between pairs of counters.

The unidirectional counter method provides us with an additional useful piece of information—the sum count—which helps establish the expected accuracy of our data. Repeated observations indicate that the accuracy of the data we get from all of our pulse-counting systems is almost equal to the accuracy predicted by statistical theory.

A pulse-counting photometer

For the 100-inch telescope at Mount Wilson we have developed a pulse-counting photometer to work with the coudé spectrograph. It contains two reversing counters, similar to the unit at Palomar, but the counters are set up for the primary purpose of measuring the ratio of light intensities.

The principle is quite straightforward. One counter is connected to a photomultiplier which monitors the background or continuum part of a stellar spectrum. The other photomultiplier is exposed, through a slit, to one point on a spectral line. When the total count in the monitor counter reaches a preset number, the scan channel count is recorded and the scan slit moves on to the next point.

This means that despite the variations in sky transparency, thin clouds, seeing fluctuations, or guiding errors, we are able to make accurate photometric measurements.

If we reverse the role of these two counters and count to the preset number for the scanning aperture, we can always ensure that we are making our measurements with constant accuracy. In other words, we spend more time collecting data in the center of a deep absorption line than we do at a point in the continuum. In this case, the count that comes from the monitor, or reference counter, must be inverted to get the ratio of these two numbers.

This 100-inch system was designed for work on the coudé spectrograph, but it was also designed to be a general purpose device. It has been used for broad-band photometry and for photometric measurements with a spectrum scanner. And we have used it with some of the infrared detectors. In this case we take the output from the infrared detector and connect it to a voltage-to-frequency converter so that we get a series of pulses. The number of pulses per second is proportional to the input signal, and we can treat this signal, as far as the counters are concerned, in exactly the same way we would treat the pulses coming from a photomultiplier.

Two sets of records

On all of these nighttime data collecting systems we use a paper tape printer to record the information onto a tape and, operating simultaneously, a printing summary punch to record the same information on IBM cards. The tape is essential because the observer needs to be able to see his results at the time he is getting them and to be able to go back two or three observations to compare new data with observations made earlier. The summary punch is valuable because the cards can be read directly into the computer with no hand manipulations.

We have also worked on the 150-foot solar tower at Mount Wilson where we are concerned with measuring the magnetic field on the sun itself. There we use a two-axis servo system in which the image of the sun follows the motion of a large ring. Two photocells, with a pair of apertures for each, generate the electrical signal for the servo system. The ring "holds" the sun accurately in its center, and, as the ring is moved in a raster pattern by means of a digital control, it is possible to scan the image of the sun over the slit of the spectrograph. The light emerging from the spectrograph falls on two photomultipliers, and their output is amplified by DC amplifiers. Because the light level is so high, there is no advantage in using pulse amplifiers.

With analogue computer techniques we generate electrical signals from which we can derive the longitudinal magnetic field, the radial velocity, and the intensity for the area of the sun which falls into the spectrograph slit. Then, using voltage-to-frequency converters and reversing counters to generate digital data, we record these data on magnetic tape in a computer-compatible format. The tapes are brought to Caltech for processing by the 7094 computer. These solar magnetograph observations result in graphical plots consisting of lines of equal magnetic field on the sun—isogauss lines.

We are developing several techniques for using automatic data reduction equipment to analyze photographic plates and convert the data into a usable form for the computer. First, we have put a digitizer on our Grant measuring engine to aid in the process of getting light measurements into the computer. Second, we are putting a two-axis digitizer on the iris stellar photometer. The iris photometer will also have a servo system so that the iris can be closed down around the star image automatically. Use of this system allows the star image on photographic plates to be converted into computer format directly and, because it is almost completely automated, greatly reduces the element of human error.

Third, we will construct a two-dimensional automatic scanning microphotometer. Its function is to scan images on photographic plates, take the output in an automatic digital form, and send these data to the computer, which converts this information into isophote lines.

The developments described so far have been designed to do specific jobs for specific instruments, like the 200-inch telescope. However, there is a class of items on which we have been working that are designed to be used for all telescopes and for all forms of observing.

Among these, designed but not yet in operation, are precision digital encoders, precision clocks, and possibly on-line computers, all of which will enable us to set our telescopes more accurately. The encoders have a resolution of approximately one second of an arc, and the clocks are accurate to one-tenth of a second of time. With these we can specify the coordinates (latitude and longitude) of the objects to be observed and can set the telescope automatically to within ten seconds of an arc of the apparent position.

Fainter stars

We also have plans, but as yet no hardware, to improve the operating efficiency of the telescope by using closed circuit television image intensifiers to help the observer locate his object and also to enable him to see stars that are fainter than those he can see in the eyepiece with his unaided eye. Experience indicates that a TV system with an image orthicon camera tube used in a storage mode should enable us to see stars that are very nearly at the photographic limit of the telescope.

Our modernization program has resulted in tangible and substantial gains. By using the automatic data recording equipment with the pulse-counting amplifiers, astronomers are able to observe twice as many stars in a specific period of time as they were able to observe with the older DC amplifier and the strip chart recorders.

By using the pulse-counting data system, an observer can get the same accuracy and confidence level in a ten-second integration as he was able to get in one minute of recording with a strip chart recorder. When the two photomultiplier tube photometer is used, the observer gets an additional factor of two in operating efficiency. Great gains have also been made by use of the computer to reduce data. The photometric data that we are getting from Palomar can now be reduced to a usable form in a matter of minutes compared with the several weeks previously required.

Another computer-use gain has been in the making of isogauss maps from the solar magnetograph observations. In a few minutes of computer time and something like 40 minutes of automatic plotting time, we are able to make isogauss maps which previously required a month or more to make. Because of the long time required in the past, few of these reductions were ever made. Now one or two per day are turned out in a routine manner.

The human factor

So far this report has dealt only with the instruments themselves. But the human factor—the relationship of the observer to his equipment—has also been more effectively refined. The equipment has been maintained and checked out before each observing run by the same laboratory personnel as those involved in its construction and design. This ensures a very sensitive feedback to the design stages of new instruments and minimizes the chances of our repeating mistakes.

Further, we have followed the principle that the systems we are designing should do exactly what the observer wishes. At all times he must be able to monitor and control his data system, but he must never be a part of the data collection chain. In that way the element of human fallibility is reduced.

For the future there is a great need for a two-dimensional photometric measuring technique which will have the sensitivity and linear characteristics of the photomultiplier system. This device will have an all-electronic, numerical output suitable for computer handling and will transmit the data directly from the telescope to the computer to eliminate the necessity for having to use a photographic plate as an intermediate data storage device between the telescope and the computer.

Beyond this are many potential techniques which could further enhance ground-based astronomy. We at the astro-electronics laboratory will not be able to foresee them all, so we must rely on others to help us, to inform us of the techniques that have been developed in industry and other laboratories, and to share their ideas with us.