

## A FULLY AUTOMATED DIGITALLY CONTROLLED 30-INCH TELESCOPE

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A fully automated 30-inch (75-cm) telescope has been successfully designed and constructed from a military surplus Nike-Ajax radar mount. Novel features include: closed-loop operation between mountain telescope and campus computer 30 km apart via microwave link, a TV-type sensor which is photon shot-noise limited, a special lightweight primary mirror, and a stepping motor drive capable of slewing and settling one degree in one second or a radian in fifteen seconds.

*Key words:* automated telescope — remote computer control — photometric imaging (2-dimensional) — light-weight 75-cm mirror

## Introduction

A completely automated 30-inch (75-cm) telescope controlled from a remote computer has been designed, constructed, and tested. The primary scientific purpose is to search galaxies sufficiently rapidly for supernovae that many supernovae may be found a few weeks old, and a few supernovae can be discovered during the first hours following detonation. Recognition that a new supernova is present should initiate taking of a series of low-dispersion spectra. A blue-shifted Planck distribution should be observed (Colgate and McKee 1969), shifting from near the velocity of light  $c$  at detonation time to  $\approx 0.1c$  hours later, from which the velocity vs. mass fraction can be reconstructed and compared with supernova models. To meet this goal of finding many supernovae each year with several early supernovae, it is necessary to search a different galaxy every 3 to 10 seconds to a limiting magnitude near 19th (1000–4000 galaxies twice nightly). Conventional photographic methods on a normal telescope followed by human comparison of galaxy fields cannot attain this rapid rate nor the immediate response needed to take spectra early in the light curve. Severe constraints are placed on the design by these requirements of high sensitivity, high speed, and immediate response.

A sufficient number of photons must be collected during an exposure and read out for a 19th magnitude supernova to appear as a statistically significant ( $5\sigma$ ) event against a background of sky, galaxy, and readout noise. Such

a high quantum efficiency combined with a readout noise negligible in comparison with incoming photon shot noise has recently been achieved by coupling a single stage ITTF4089 image tube with an RCA4826 SIT VIDICON tube (described in Colgate, Moore, and Colburn 1975). The television readout is a single digital scan requiring one-third second of time. At the end of each exposure the digital information corresponding to a square array of  $128 \times 128$  elements of intensity is sent via microwave link (Appendix) to the memory of the IBM 360/44 campus computer 30 km away for immediate reduction and response. In order to minimize the effects of readout noise, the amount of information to be transferred to the computer, and sensor nonlinearity, it is desirable that the sensor image element be roughly the average seeing resolution of  $\approx 2$  arc seconds. Then roughly 50% of a stellar image intensity falls in four picture elements and 85% in nine elements.

This desired sensor performance specifies the 30-inch (75-cm) telescope aperture. A smaller aperture telescope cannot gather enough photons in 3 seconds, a larger aperture telescope with its larger moment of inertia is more difficult to slew rapidly and is much more expensive. The moment of inertia is minimized by choosing a focal ratio of  $f/3$  for a centrally supported lightweight paraboloidal primary. The final equivalent focal length of 900 inches (22.5 meters) is derived from the above condition that the average stellar seeing disk diameter of 2 arc seconds be equal in size to one TV image ele-

ment, 1/128 inch. This  $f/30$  focus behind the primary mirror in the usual pierced Cassegrain position is achieved with an oversized convex hyperboloidal secondary roughly 80 inches from the primary. An optional  $f/12$  focus at this same image-tube position is provided in a Merseenne configuration. Also, flat mirrors may be inserted in order to divert the  $f/30$  beam to a spectrograph (to be discussed in another publication) and bring the output into focus again onto the same image tube. The 30-inch (75-cm) telescope with the present sensor requires a 4-second integration time to reach 18th magnitude and one second to slew to the next galaxy. A SLO-SYN® stepping motor on each of the equatorial axes is capable of sidereal tracking at one arc second per step during exposure, of slewing the average one-degree angle between search galaxies and then settling in less than one second, and of slewing a radian and then settling in less than 15 seconds.

#### The Military Surplus Nike-Ajax Mount

In 1966 the development of a new telescope mounting to meet the necessary specifications would have been prohibitively expensive, but fortunately a surplus Nike-Ajax radar mounting could be sufficiently upgraded.

The mount shown in Figure 1 was designed originally to hold several hundred pounds of radar equipment and to slew very rapidly in alt-azimuth for tracking military targets with an accuracy of  $10^{-4}$  radian. It was made of webbed magnesium castings and designed for extreme rigidity for rough terrain travel. Consequently, though the radar pointing accuracy was modest, the bearing clearances were exceedingly small. A side thrust of 1000 pounds either normal or parallel to the declination axis deflected the yoke only 0.010 inch.

Figure 1 also shows the mount tipped up into equatorial position with the secondary support cage installed. When the mount was used for radar service in the alt-azimuth position the horizontal plane was determined by rollers on an azimuth track. The vertical axis was maintained by an accurate 18-inch diameter bearing. The rollers on the track were not sufficiently accurate for an optical telescope, but the main bearing was. We added an aluminum shaft 8 inches outside diameter by 4 inches inside diameter that

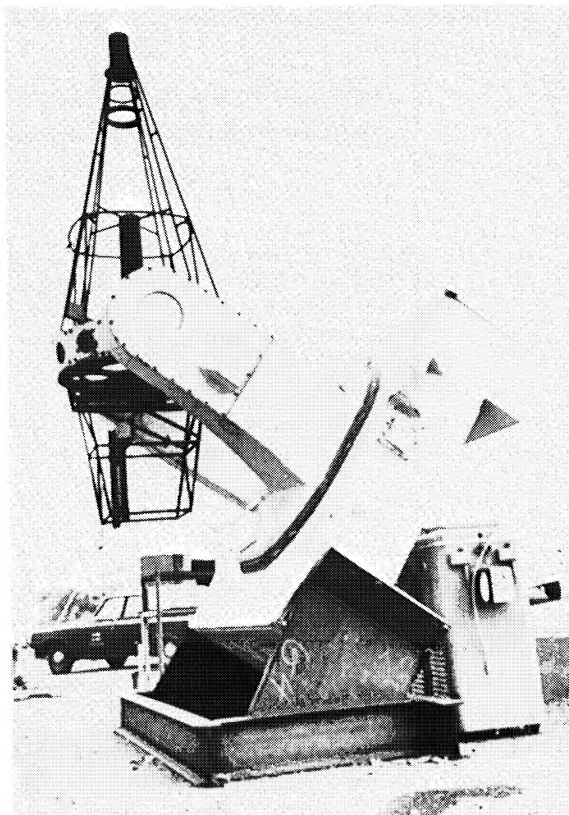


FIG. 1 — This photograph of the fully automated telescope taken before exterior baffling and dome installation shows the secondary at top, secondary's support cage, primary's interior light baffle, 30-inch (75-cm) primary's cell, rear support cage for spectrograph and image-tube equipment, magnesium fork arms and base, and the auxiliary steel base to convert this military surplus Nike-Ajax radar from an alt-azimuth to equatorial mounting.

extended the polar axis three feet beyond the main bearing to an additional small thrust polar axis bearing located in a spar at the base of the mount.

Figure 2 shows the location of the optical components, light baffles, spectrograph, and TV sensor within the yoke.

#### The Telescope

The lightweight centrally-supported mirror is shown in section in Figure 3. The section thickness as a function of radius is designed (by Henry L. Giclas, Jr. of New Mexico Tech) so that the internal stress is constant. Don Loomis of



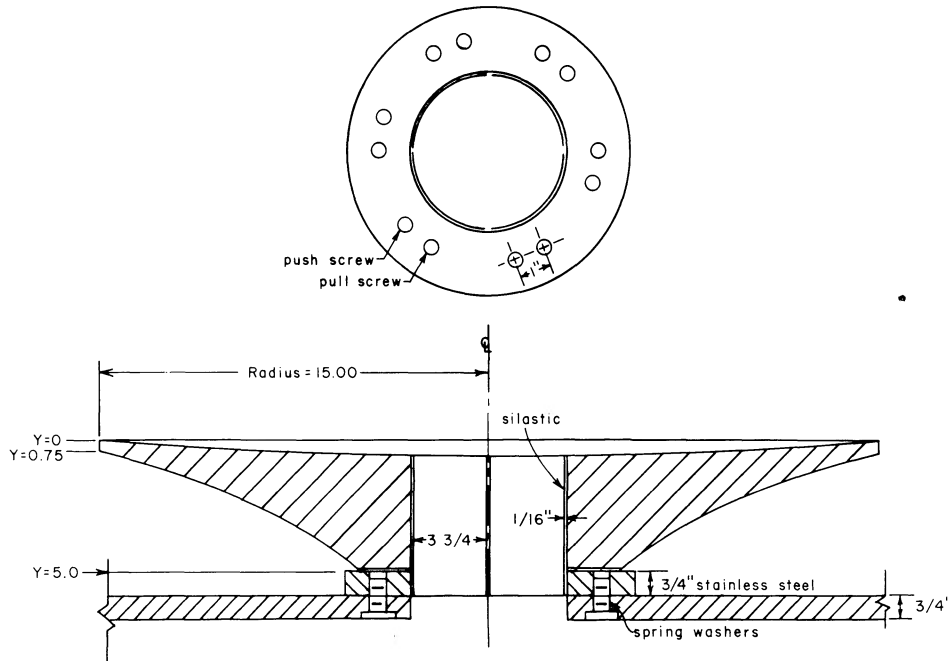


FIG. 3—Lightweight glass mirror to minimize the telescope's moment of inertia. The back of the 30-inch (75-cm) primary of Duran 50 is ground to the shape shown, with equal and constant stress throughout. The supporting mirror cell is a stainless steel back plate, with 6 push-pull pairs of screws for collimation, and a central  $1/16''$  stainless steel tube. Both are glued to the mirror with Silastic RTV Silicone rubber.

tending 19 inches from the secondary. A second cone extends from the 7.5-inch diameter hole in the primary toward the secondary mirror. A cylindrical outer light shield "telescope tube" with ring baffles,  $\frac{2}{3}$  the distance from the primary to the secondary, was added to reduce a major problem encountered with scattered light. This tube increased wind loading considerably and may eventually require replacement of our clamshell dome (which dissipates heat easily and does not require an automated dome to "track" the telescope at high speeds) with a conventional slit dome.

The Nike-Ajax radar mount had a highly accurate gear on both axes that engaged a gear box for dial-readout indication of angular position. These gear trains were made with antibacklash gears which showed no backlash to  $\pm 0.1$  arc second and had a uniformity of motion over a period of a major tooth engagement of  $\pm 1$  arc second. We therefore decided to drive the existing readout-dial gear train backward using a stepping motor open loop, that is, without position feedback from the telescope. We replaced the antibacklash springs of the first gear associated with

the dial gear train to achieve an antibacklash torque of approximately 1000-inch-pounds at the telescope to stiffen the drive train. In addition, the first shaft in the dial-readout gear train was stiffened by an overlay of fiberglass epoxy. Figure 5 is a sketch of the gear train, the SLO-SYN<sup>®</sup> motor, and the optical shaft encoder for the motor feedback.

### Slewing Motors

Radio telescopes, as well as the original Nike-Ajax radar mount, utilize torque motors with feedback from angle encoders. Digital encoders are used for digital servo systems. This relatively mundane sensor arrangement dictated our slewing system design. To implement the supernovae search program, we needed to have an absolute position accuracy of one-quarter field of view or one arc minute (ideally one arc second setting accuracy). Digital encoders with the needed accuracy doubled the estimated cost of the drive at the time this project was initiated, so we chose to develop a slewing system based upon incremental stepping motors. Absolute positioning is determined initially by micro-

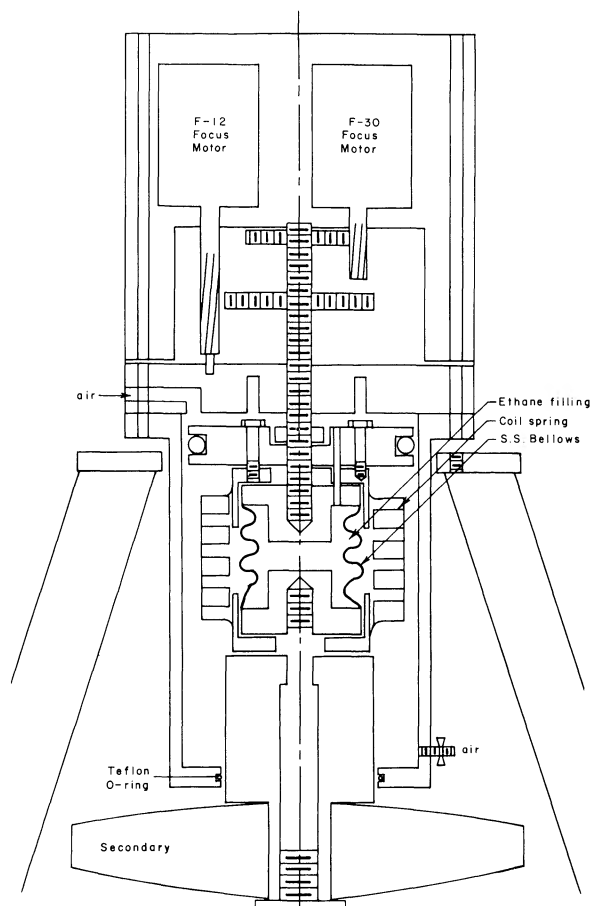


FIG. 4—Schematic diagram of the secondary mirror assembly. The 4.5-inch (11.5-cm) diameter Cervit secondary is shown held at its pierced center to an inner cylinder containing a spring and a bellows filled with ethane gas in equilibrium with its liquid. The combination temperature-pressure displacement nearly compensates the effect of diurnal temperature variation on telescope focus. When so commanded by the computer the system changes between  $f/12$  and  $f/30$  foci in a few seconds by allowing compressed air to enter one of the two inlets, shifting the inner cylinder with secondary toward or away from the primary about an inch while simultaneously inserting or removing a lens (not shown) behind the primary. At the top of this figure are the separate motors for fine adjustment of each focus (used only after large seasonal temperature changes).

switches, checked by field stars using the image tube, and corrected by computer software. Positions relative to that position are determined by digitally counting the number of steps from the switch to the star and adding the stellar correction (in the computer).

A single stepping motor per telescope axis is

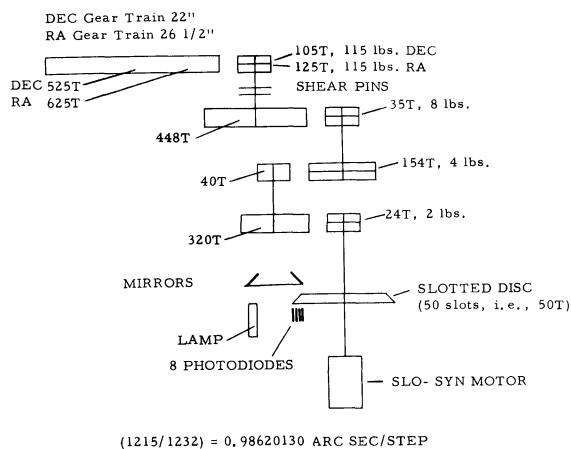


FIG. 5—Schematic diagram of gear train and stepping motor. A single motor and gear train with a continuous speed range from zero to sidereal rate to a maximum of 12 degrees per second is used instead of the separate tracking, guiding, and slewing motors with clutches customarily found in telescope drives. The gear trains shown for right ascension and declination each yield roughly one arc second for each step, although the two gears closest to the telescope differ in the two trains. The preloading of each antibacklash gear is expressed in pounds. Thus, the preloading of the first gear of 115 pounds at 11-inch declination gear radius gives an antibacklash torque at the telescope of 1250 inch-pounds or  $\approx 1400$  kilogram  $\text{cm}^{-1}$ .

used for holding (stopped), tracking, guiding, and slewing (stopped), tracking, guiding, and slewing rather than the customary two or three motors and various clutches found in classical telescope drives. The dynamic range of our motors is continuous from zero (stopped) to sidereal rates to the motor peak speed of 12.5 degrees per second.

In normal use of a stepping motor without an acceleration ramp and at rated winding voltages (and currents), the motor torque limits the maximum speed to 150 to 300 steps per second. We required a maximum stepping speed of 20,000 steps per second (1 arc second per step) to slew one radian in 10 seconds as required by the supernovae search. This speed was 50 to 100 times the current state of the art, and we also did not know whether we would encounter excessive vibration when driving the gear trains at sidereal rate (15 discrete steps per second), so we ascertained that each step could be further subdivided into 10 subincrements by programming the current in the windings. In other words, we designed the system with one arc second per step, but held in reserve the capability to reduce the

step size by a further factor of ten. We have not required this additional accuracy to our stepper motor windings which are entirely digital in nature.

Using a shaft encoder and logical feedback our present peak speeds are 20,000 steps per second and the time to slew one radian is 15 seconds or to slew one degree is 1 second, as required for the supernova search program. Figure 6 shows the basic performance of the drive as produced by the computer control of the telescope before overshoot correction has been made.

### The Digital Drive Controller

Right ascension and declination electronics are identical for hardware simplicity and debugging (i.e., interchangeable). This also allows independent tracking with two digitally addressable 16-bit clocks. Tracking direction is also selectable so the telescope can be simultaneously

tracked east or west *and* north or south.

Motor acceleration is controlled by adding an appropriate 3-bit number to the present (NOW) position of the motor shaft as determined by the shaft encoder, Figure 7. The highest acceleration is in the 8-step mode adding plus or minus three (binary 011 or 101) to the present step, while the highest speed is in the 4-step mode adding plus or minus four (binary 100). The greatest deceleration is in the 8-step mode adding zero binary (000) to the current motor step. Tracking is done in the 8-step mode adding plus or minus one (binary 001 or 111) which gives minimum acceleration to reduce tracking overshoot. (The Superior Electric Company which manufactures the SLO-SYN<sup>®</sup> motor is now using the terms full-step mode for our 4-step mode and half-step mode for our 8-step mode. There are 50 8-step cycles per motor revolution.) The feedback from the shaft encoder can be disabled and the counter inputs used to align and

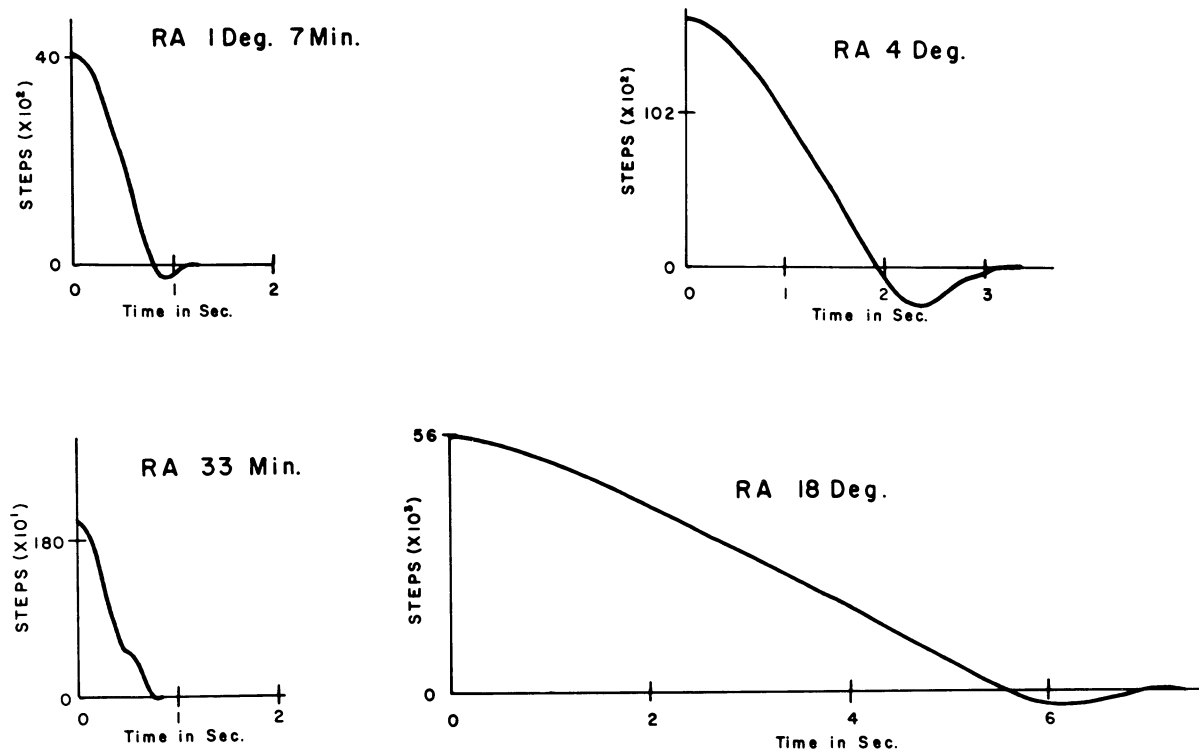


FIG. 6 — The basic performance of the stepping motor and its controller attached to the telescope is illustrated in these computer-produced plots from data taken during actual slews. The slewing and settling time is less than one second for a half-degree slew, about 1.2 seconds for a 1.1 degree slew, and about 7 seconds for 18 degrees (one-third of a radian). In this basic performance the telescope overshoots its final position and returns; in astronomical use there is continual interaction during the slew between the IBM 360/44 campus computer and mountain controller, reducing the total time to about that shown at the first minimum on each graph.



scope position and power supply voltages, may be queried digitally. Comprehensive software to automatically diagnose failures (and lack of failures) greatly simplifies hardware maintenance and repair.

Several developments now indicate that a very much simpler system is feasible. At least two minicomputers are available for less than \$1,000. The same stepping motor manufacturer has announced open loop motor drives and motors that are capable of speeds of 20,000 steps  $\text{sec}^{-1}$  that require a single pulse per step from a minicomputer. The minicomputer can generate its own acceleration or deceleration-ramp open loop such that allegedly no steps are missed, and the complexity of closed loop encoder circuitry can be avoided. Today such a digitally controlled system would cost roughly 1/10 to 1/2 that of our current system and would be far more flexible. In the laboratory, we originally tried to drive our stepping motors open loop to the necessary high speeds but found that many steps were dropped unless the acceleration ramp was very carefully controlled. A more detailed report of the stepping motor drive is available upon request.

#### System Operation

The telescope is designed to be controlled in a closed loop by the computer with minimal intervention by a human operator 30 km away. An operator can control the system by pushing one of several computer interrupt buttons, by typing commands to the computer on a teletype® to transfer control or data to a stored program, or by directly setting and querying individual registers off-line on a manual system of switches. The operator can monitor the system and actions by watching the pictures automatically displayed on a CRT monitor as they enter the computer, by asking for computer-processed data on a different CRT monitor, and by listening to actions in the dome via audio modulation on the microwave link. The system software (to be described separately) now consists of the equivalent of approximately 100,000 FORTRAN statements. With completion of the hardware in late 1974, we are now completing and starting tests of the software necessary for the real time supernova search.

#### Other Automated Telescopes and Supernova Searches

Single-channel photoelectric photometry of bright stars for extinction and sky brightness with a fully automated 8-inch telescope has been carried out for many years at the University of Wisconsin (McNall, Miedaner, and Code 1968). More general-purpose fully automated telescopes now in operation or under construction include the 24-inch at Michigan State University (Hill and Linnell 1974) plus the 16-inch and 24-inch at MIT's Wallace Observatory (McCord, Snellen, and Paavola 1972). An earlier 50-inch at Kitt Peak (Hudson et al. 1971; Maran 1967) encountered difficulties with excessive innovation but achieved significant results in the necessary repetitive measurements needed to obtain the light curve of the  $\delta$  Scuti star 14 Aurigae.

Other supernova search programs include those at Palomar with the 48-inch and 18-inch Schmidt telescopes (Sargent, Searle, and Kowal 1973), at Asiago in Italy with a 40-cm Schmidt telescope (Rosino and DiTullio 1973), and at Konkaly in Hungary with a 60-cm Schmidt telescope (Detre 1973). The Schmidt camera photographic searches are still finding the majority of supernovae, but the time-consuming process of exposing, developing, and manually comparing films or plates with a previous exposure prevents taking additional data as immediately as needed to follow a supernova immediately after detonation. Simple statistical calculations indicate that decades of dedicated search on any of these instruments would be required to find a few supernovae within hours after detonation; they are most efficient at finding supernovae after maximum light for other research objectives.

At Corralitos Observatory in New Mexico, operated by Northwestern University, Hynek and Dunlap (private communication; Hynek 1971; Hynek and Dunlap 1973) have achieved the first operating semiautomated supernova search program with 24-inch and 16-inch Cassegrain telescopes. A computer automatically sets the telescope on a galaxy, takes a TV picture, and presents the image immediately for comparison with a previously stored picture. Although the comparison is performed visually by an observer, this program gives the fastest response so far and in one instance (Dunlap and Dunlap 1975) recognized a supernova 10 seconds

after the second picture was taken. The previous comparison was made 9 days earlier. The Corralitos facility combines our joint requirements for immediately knowing a supernova is present with the high quantum efficiency of the photoelectric process allowing many galaxies to be searched, but does not yet reach the thousand galaxy per hour rate required to find a few supernovae per year shortly after detonation.

### Conclusion

We believe we have demonstrated a unique design for a remote-controlled digital telescope using considerable surplus components with the capability of slewing rapidly (1 radian in 15 seconds) and accurately ( $\pm 10$  arc seconds radian<sup>-1</sup>) to computer-directed objects. It is particularly suited to repetitive measurements.

The digital television system is described in Colgate, Moore, and Colburn (1975). Spectrograph and software will appear in separate publications. The microwave link and computer interface are described in the Appendix.

The engineering for much of the telescope and lightweight mirror shape was by Henry L. Giclas, Jr., for the gear trains by Al Bartlett, the telescope construction supervision by Kyle Dillard and Luther Weeks. The mirrors were figured by Don Loomis of Tucson and aluminized by Kitt Peak National Observatory. Joe Aloway designed and constructed much of the secondary-mirror mount and auxiliary instruments. John Colburn and many students and staff helped with construction and design of the extensive electronics as well as the assembly and construction on the mountain. Among these are: Paul Merillat, Danny Pilkenton, David Warner, April Stevenson, Mike Price, Harry Muttart, Bryan Edwards, Bruce Ashcroft, John Koster, David Lewallen, Dan Hendry, Tom Lawrence, Jeffrey Colvin, Tom Greene, and Joseph Medley. Extensive conversations are gratefully acknowledged during the initial design phase with Steve Maran and Pete Vokac then of Kitt Peak National Observatory, and with Allan Hynek and Justus Dunlap of Corralitos Observatory. The contribution of Adrian Webster of Berkeley is also acknowledged.

Extensive discussions with Larry Burris of Boller and Chivens convinced us of the neces-

sity of building our own mount in view of the state of the art and budget at the time. Finally, the original enthusiasm of Gerald Mulders of the National Science Foundation and the subsequent funding of grant no. GP-27698 by NSF has supported this project for the first six years of its existence and recently partial support through the NASA-Goddard Space Flight Center/New Mexico Tech Agreement is acknowledged.

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### APPENDIX

#### Microwave System

The telescope with its television sensor is operated remotely at Langmuir Laboratory for Atmospheric Research on South Baldy peak at 3220 m (10,500 ft) in the Magdalena Mountains, 30 km west of the Socorro campus of New Mexico Tech. The search function depends upon real-time processing of a digital image so that a major computer is required. The data exchange is accomplished by a microwave link of somewhat novel de-

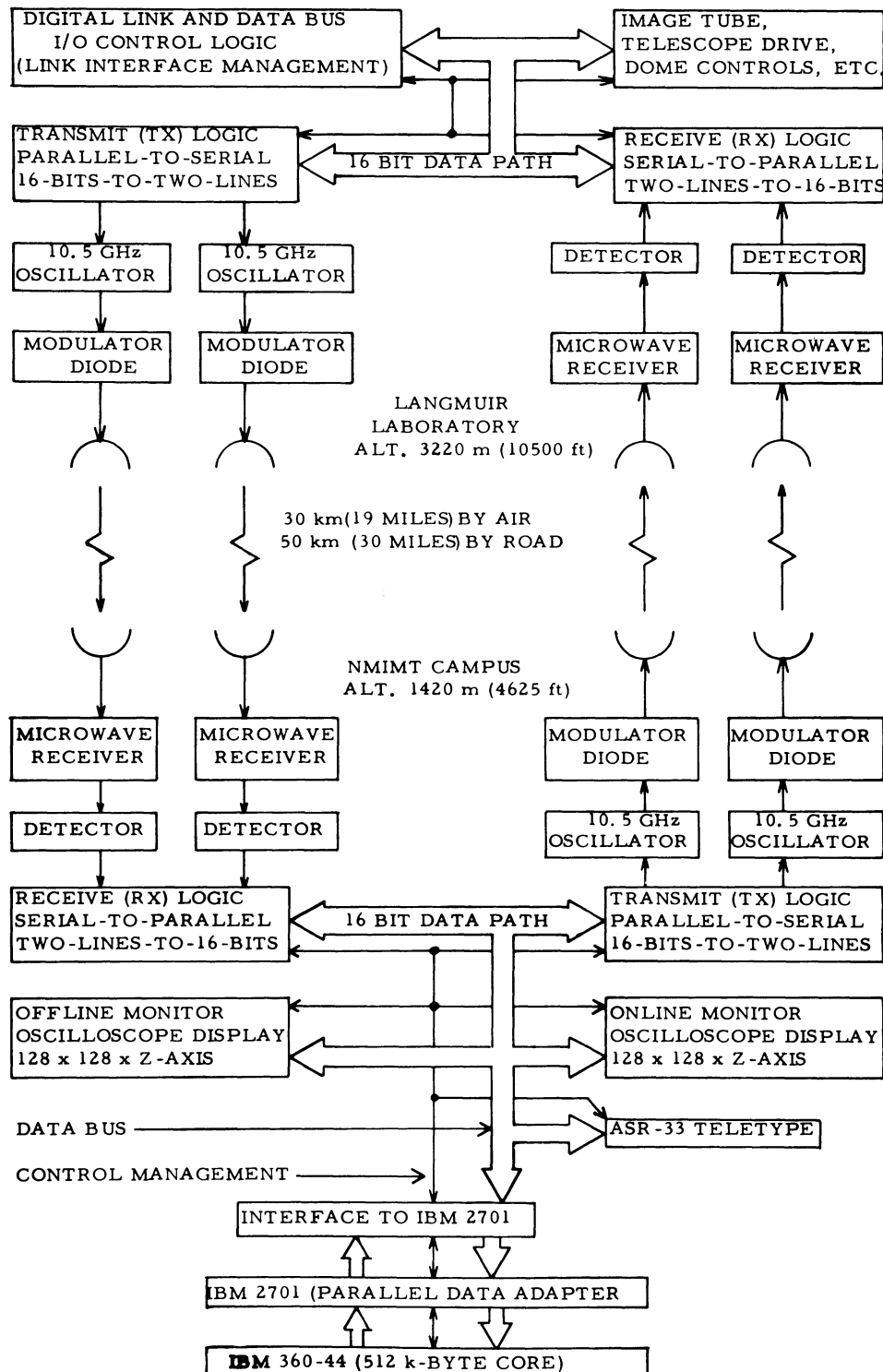


FIG. 8—This block diagram of the Digitized Astronomy and Supernova Search program shows the IBM 360/44 (with 512 kilobytes of core) with interface to operator controls at the New Mexico Tech campus 30 km (19 air miles) from the telescope located on South Baldy Mountain in the Magdalena Mountains near Socorro. A highly redundant microwave link transfers 25,000 16-bit digital words per second to and from the image tube controls (ITT F 4089 intensifier coupled to an RCA 4826 SIT vidicon), the clamshell dome controls, and the 75-cm digital telescope controls.

sign and modest cost that allows simultaneous sending and receiving of data as well as voice communication. Two simultaneous microwave channels are used in each direction giving 4 allowable states to the system. "00" is forbidden, 01 and 10 are the binary data states and 11 is the asynchronous transfer state. The 16-bit word is bracketed by a beginning-of-word and end-of-word sequence and transmitted serially at  $5 \times 10^5$  bits per sec to the two channels of each transmitter modulator. The transmitters and local oscillators are 25 milliwatt impatt-diodes. The receive logic is the inverse of the above. A set of offline switches for sending, lights for data dis-

play, and a display oscilloscope allow partial operation without the main computer. Figure 8 is a block diagram showing the digital interface between the IBM 2701 Data Adapter and the RX-TX (receive and transmit) function. This interface was designed and constructed with RTL components by Richard Krasin before minicomputers cost less than \$10,000 and has operated with RTL logic successfully since. The system has operated for months at a time without attention. The error rate is detected by parity encoding each of the 16,000 bytes of a TV picture. The error rate is currently less than one bit in  $10^8$ .