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CONTROL SYSTEM FOR PARABOLIC DISH CONCENTRATOR NO. 1

By
J. A. Stallkamp

March 15, 1985

Work Performed Under Contract No. AM04-80AL13137

Jet Propulsion Laboratory
Pasadena, California

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ABSTRACT

This report is a description and discussion of the control system for Parabolic Dish Concentrator No. 1 (PDC-1) as used at the JPL Parabolic Dish Test Site (PDTS). The tracking action is a discontinuous, start/stop motion with sun sensors for primary control and a computed sun ephemeris for a simultaneous check and cloud passage. Project background, functional requirements, and hardware description are presented in brief form. System operation is described in considerable detail and includes the precise message exchange protocol between the module and remote control station, the initialization process, the command list, and the basic control logic used in the local microprocessor. System installation and performance items are given; the unit operated very satisfactorily for the brief period of time before it was moved to Sandia National Laboratories at Albuquerque, New Mexico. It was operated at a 0.05-deg deadband for optical characterization of the reflecting surfaces and mirror geometry. The last section includes significant presentations and discussions of (1) protection against burn by the sun in the case of failure to continue to track and (2) other equipment and personnel safety items. Operation of PDC-1 at the test site was man-attended; for extension to man-unattended operation a number of additional requirements and constraints must be identified and a full implementation of the capabilities of the design be performed.

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SECTION I

INTRODUCTION

This document describes the control system of Parabolic Dish Concentrator No. 1 (PDC-1) installed at the Parabolic Dish Test Site (PDTS)[1] operated by the Jet Propulsion Laboratory at its Edwards Test Station, Edwards Air Force Base, California. Emphasis is given to those aspects that are considered to be unique to this unit, viz, the use of a start/stop rather than a continuous tracking motion and the dual control of this motion. The latter is done first by sun sensors for the fine, more accurate track of the sun and second by the comparison of a calculated position of the sun with measured azimuth and elevation angles for the coarse, less accurate track. In normal operation both tracking systems are in continuous use, with the first providing the prime control and the second acting as a failure check on the first and providing the actual tracking during cloud passage.

Additional unique features include a rapid, slewing, motion capability for transfer between an offset track mode and the on-sun modes. During this motion the fireball image of the sun must pass between the major support structure and quickly cross the aperture plate shielding the power conversion assembly located at the main focal point. This rapid motion is brought to a controlled stop with the image of the sun at or suitably close to the center of the aperture. Operational safety is provided by a rapid detrack motion, which is essentially the reverse of the acquisition motion just described.

The control system successfully operated the PDC-1 unit at the PDTS. It was to be adapted to a PDC-2 unit to be built by Acurex Corporation. The original plan was to build units of these types in groups for fully automatic, man-unattended operation as solar electric plants. The digital control system was originally designed for this type of operation. However, the complete capability was not implemented at the PDTS. The successful operation there was from a man-attended remote console. Shortly after the start of testing it was found that the original azimuth wheel bearings were undersized. They were gradually destroyed during initial operation; the control system operated very satisfactorily during the deteriorating situation. Later, optical characterization of the unit was performed; again the control system performed totally satisfactorily. In the spring of 1984, PDC-1 was disassembled and shipped to Sandia National Laboratories in Albuquerque, New Mexico.

PDC-1 was designed by the General Electric Co. (GE), Valley Forge Division. The control system was also designed by GE, and the first articles were built and partially tested by them. Upon termination of the contract, these control system items were delivered to JPL in an as-is state. They were completed, assembled, and tested at JPL. They were then incorporated into the mechanical and optical structure built from GE drawings under the direction of Ford Aerospace and Communications Corporation. A few significant modifications were made by JPL in both hardware and software along with a host of

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[1] Other activities carried out at the PDTS are described in Reference 1.

minor changes. However, the original GE-supplied equipment was used for the most part, often just as delivered; most of the modifications were the normal result of development checkout and would have occurred independent of where or by whom the work was completed. The control system remains the basic GE design.

An extended description of the PDC-1 concentrator is given in Reference 2. For purposes here, a brief mechanical description highlighting the moving parts is now given. Figure 1 in the appendix is a general view of the concentrator. The configuration is elevation over azimuth. The azimuth track is a deep I-beam circle about 41 ft in diameter. The rotating azimuth base frame is a hexagonal tubular structure constrained in the center by a pintal bearing in a large concrete anchor block. At opposite ends of a diameter, a vertical tubular structure provides the support for elevation bearings at about 25 ft above the ground. The parabolic reflecting surfaces are plastic panels with inside (reflecting side) ribs, all of which are integral parts of the elevation axis structure. A quadripod structure extends forward and another rearward from near the mirror edge; two legs are near the elevation bearings and the other two extend from points midway around the edge of the mirror. The forward quadripod structure supports the equipment at the focus, and the rearward holds a counterweight so that the elevation axis can be approximately balanced. Azimuth drive motion is provided by means of a tensioned steel wire cable about 5/8 in. in diameter that is wrapped around the outside of the I-beam track; it is picked off the I-beam and driven by pulleys and sheaves mounted on the moving azimuth platform. The unit thus pulls itself around in azimuth along this fixed cable. This azimuth drive is the square object in the lower center of Figure 1. It has a range of about 330 deg between limit switches. The elevation drive uses a similar cable contained in a trough held in a large diameter semicircular configuration supported from a rearward and a forward facing quadripod leg. The elevation range is 180 deg from straight down to straight up.

Figures 2 and 3 in the appendix show some of the control system hardware. Several of the items referenced later in the text are identified here. Figure 2 is the Concentrator Control Unit (CCU). It is mounted on the farside (outside) of the square plate attached to the vertical tubular structure that appears in the left side of Figure 1. Located at the equivalent place in the right side of Figure 1 are the motor controllers (upper left white box) and the primary, standard push-button, local drive stations (below the white box). The other boxes here are for test instrumentation. Returning to the CCU in Figure 2, the top panel is the local manual control station that actually was used only while adjusting the tracking control system. Under this panel is space for control boards. The four relay boards are in place. Two synchro translator boards and the sun sensor electronics are not in place. The lower half of the CCU contains the microprocessor board on the left and the input/output ports on the right. This CCU box was contained in a watertight NEMA enclosure and powered from an external circuit breaker located adjacent to the enclosure. It was not necessary to enter the enclosure for normal operation. The CCU was locally self-initializing at power turn-on.

Figure 3 shows (from left to right) the remote control station (CCR), one of the synchro units, and the tall, slender sun sensor. The elevation synchro was mounted outboard of the elevation bearing shown in the right side of Figure 1. The sun sensor was located on the quadripod leg extending from near the elevation bearing in the left side of the same figure. The CCR together with the remote control computer and its display and keyboard input were located in a trailer adjacent to the unit. Remote control, as distinguished from primary local control from push buttons adjacent to the motor controllers, could be done in three ways selected by the AUTO/MANUAL and CCU/CCR control switches: manually at the CCU, manually remotely at the CCR, and automatically using the remote computer and local microprocessor. Under manual control the unit could only be moved from one fixed pointing direction to another. The automatic system was required for tracking control.

SECTION II

REQUIREMENTS AND FUNCTIONAL DESCRIPTION

There were three key operational considerations and constraints that determined the approach to this control system. First was the requirement that the unit acquire and depart the sun at a rapid slew rate on the order of 2 deg/s. Second, the unit was not required to track the sun with a continuous motion but only to keep the fireball image of the sun within 0.1 deg of the optical axis and this only when the sun was above some nominal intensity. Third, the unit could track the sun within a deadband greater than 0.1 deg when the intensity of the sun was low (e.g., the sun was behind a cloud) and then must rapidly reacquire operation to within 0.1 deg when higher intensity returned. These requirements were in direct contrast to the characteristics of the test bed concentrator (TBC) at the PDTS, whose very slow acquisition rates required the use of a water-cooled aperture plate including a water-cooled sliding door to protect equipment during its very slow slews onto and off of the sun. On the other hand, the TBC's sharper image-forming capability from its individually adjustable mirrors justified a continuous and more accurate tracking capability; the PDC-1 unit was not capable of the high concentration ratio achievable by the TBC units.

Other requirements may be conveniently grouped into two categories and then only briefly mentioned here. Under operation considerations, modules were ultimately to be remotely controlled either singly or in groups. A module would consist of the concentrator and the power conversion assembly at the focus. Under a project goal of low cost, the control system was to be as simple, as easy to maintain and service, and as inexpensive as possible. As stated, tracking performance was to be appropriate to an energy-gathering system of moderate concentration ratio.

The overall functional capabilities of the control system as finally implemented are summarized as follows:

(1) Independent elevation and azimuth motions.

(2) High-speed slewing motion of about 1.7 deg/s for acquiring and departing the sun and also for moving to and from three fixed-coordinate directions, including the down facing stow position for wind survivability.

(3) On/off tracking motion while on sun. The unit remains motionless most of the time (90% and more) and then moves at a nominal rate of 0.1 deg/s to remove the pointing error when it has reached a preset magnitude.

  (a) An auto track mode in which the unit is returned to the direction of the sun when the error reaches 0.1 deg. Conventional photo-resistive sun sensor units are used. This mode ceases to operate when the intensity of the sun falls below a set level; drive signals from the sun tracker are inhibited during these times.

(b) A coarse track mode in which the unit follows a calculated position using angle position sensors for azimuth and elevation. The deadband for this motion would be set to greater than the 0.1 deg of the auto track mode; values of 0.3, 0.2, and 0.15 were used.

(4) An offset track mode in which selected offset angles are inserted into the coarse track calculations. Motion to and from the sun and this offset position provides for a defined path for acquisition and leaving the sun; this keeps the image of the sun from impinging on the support structure.

(5) A detrack motion in which the unit moves at the slew rate for a fixed period of time that is determined by hardware external to the microprocessor control unit. This is the primary emergency action that moves the unit off the sun to a thermally safe position. It is activated internally if the unit is in one of the sun track modes and the error between the measured and the calculated position of either axis is greater than a preset value; 0.5 deg was used. It is also activated by other failure conditions internal to the control system or by external command.

SECTION III

CONTROL SYSTEM HARDWARE

Although this section focuses on hardware, comments on software will be included. This also will be done in the Control System Operation section (IV). A full, detailed listing of the software program is not appropriate for this report. In addition, these last sections will contain comments that are hoped will be useful to a person doing a similar solar concentrator controls task.

A one-line block diagram of the control system as implemented would start with a remotely located command computer with conventional status display and keyboard input capability (see Figure 4 in the appendix). The remotely located equipment is connected via a digital link to the local microprocessor at the concentrator. This RS232 link is used for commands and status only; all actual control functions are done locally at the module. The local microprocessor interfaces with electrical control hardware, i.e., relays and sensor electronics. This assembly constitutes the concentrator control unit (CCU). Motor drive commands are generated by relay closures in low voltage dc control circuits that are part of conventional, commercially available dc motor controllers. These controllers take power from 3-phase, 60-Hz mains and supply the required dc power to the motors. Direct current motors of about 3-hp capacity with integral speed reducers are used. Because the concentrator is relatively statically balanced, the power rating was sized for driving to a safe stow position under wind loading at the slew speed. No brake or holding functions are required; however, positive acceleration and deceleration rate control from the motor controllers are used. As implemented, the dc motor fields were left on at all times whereas for an actual solar plant this parasitic energy could be saved during the long off portion of the tracking cycle.

Speed is commanded by setting the voltage of an input speed wire from low dc voltages that originate in the motor controller using switches, relay contacts, resistors, and potentiometers. The motor control circuits are thus electrically isolated from the microprocessor and other input sensor circuitry. Two fixed speeds are used; one is a high slew speed and the other a low speed for the on/off tracking action. Small DIP (dual inline package) relays mounted on standard circuit boards are used. The four-pole relay supplied by GE was found to be unreliable and replaced. Fortunately, this was discovered in bench testing rather than in the field.

The additional parts failures are reported here. In addition to the relay failures cited above, the only other verified part failure in the computer control portion of the system involved one of the synchro translators. One of the dc motor controllers had a control card failure. Also in the field there was indication of intermittent operation or failure under some low temperature conditions for several digital chips in the microprocessor. This was never fully determined because the exchanged digital components would operate when reinstalled in the system under at least similar cold conditions.

The weather conditions at the PDTS on the Southern California high desert are moderately severe. Freezing temperatures can occur at night, and there is extensive moisture condensation that seems to occur almost any time.

Synchros with 14-bit output are used for azimuth and elevation position measurement. They give a resolution of about 0.02 deg per least count. The synchro shafts are connected to the main shaft hardware with small flexible bellows. The synchro mounts were very carefully adjusted to remove a small nonlinear angular rotation that was discovered at first checkout.

The sun sensor was commercially available from Mann Russell. GE purchased a modified version that supplied only drive-direction signals. JPL restored the sun intensity level measurement in order to inhibit the drive signals when the intensity of the sun decreased significantly. There were moisture condensation problems with this unit at the test site; however, because the photo-resistive elements were sealed in glass, it was only necessary to dry out the unit. For each channel, two resistive sensing units with two fixed resistive units are operated in a bridge, and the final fine adjustments of the width and location of the deadband are done on the ground in the CCU.

The microprocessor is an AMD 4006 unit with an AMD 9511 arithmetic chip. Floating point arithmetic is used only for the calculation of the position of the sun. This was done on a one-second interrupt basis; once initialized, the processor kept track of time in its own clock. Caution: When accumulating time from a one-second clock signal, do it directly; do not divide by 3600 first and accumulate in hours because the round-off error will cause fatal problems. Comment: Stable oscillators that are slightly outside of their advertised accuracy can be readily used by selecting a slightly adjusted number in the clock divide-down string. Hopefully, the next time, other things like these will not occur simultaneously. There were fatal arithmetic flaws in the original sun ephemeris program; it was redone using a much simplified arithmetic approach that needed much less permanent memory space and operated faster (Reference 3). Speed and space were not considerations here but could have significant value in other applications.

Of the 48 parallel I/O (input/output) ports, 28 are used for the two synchro inputs, 8 for drive commands, and 3 for the detrack, detrack reset, and hold-and-read synchro functions. Several spare ports would eventually have been activated; several very desirable features that will be discussed later would have been incorporated into the system had it remained at the PDTS. The four commands for each drive are motor on/off, high/low speed, forward/reverse direction, and control from sun sensor/computed position. The sun sensor drive commands go directly from the sensor electronics to the relay logic and not through the microprocessor. From operational experience, these signals should go through the processor so that some desirable timing adjustments could be made by means of software parameter changes; full details are given in Section V.

SECTION IV

CONTROL SYSTEM OPERATION

The original contract for PDC-1 called for the delivery of three units to be operable individually or in combinations from a single remote station with or without an unspecified power conversion assembly (PCA) and its (the PCA's) unspecified control system. In an ultimate solar plant, the combining of the CCU and the PCA control into a single, module control would not only be desirable but probably inevitable. The control system evolved by GE did have this extended adaptability. It did operate in a stand-alone mode at the PDTS. It was in the process of being incorporated into the Rankine-cycle PCA control system, which used a different microprocessor (Reference 4). Additionally, it was to control a radically different PDC-2 concentrator;[2] this unit was to be built on a pillar base and not gravity-balanced. At the termination of effort, this work was in progress without any identified significant problems. The indication is that this PDC-1 control system design is sound and adaptable.

The actual concentrator control function is implemented at each unit using a microprocessor with sun and mechanical position input sensors and output relay contacts that drive conventional motor controllers. Several manual control locations are available for moving the unit from one fixed pointing direction to another; relevant items will be discussed in the next section under safety (Section V). The microprocessor is required for all tracking modes. During these operations, communication with the outside world is an RS232 digital command and status link to the remotely located central computer. Having accepted a valid command from central control (e.g., going from stow to offset track is valid; going directly from stow to a sun track is not), the CCU would execute this new command. The unit would first go to the new position. If it were a tracking mode, it would continue the tracking action as long as it were able, subject to mechanical limits or the arrival of a new command. All parameters for accomplishing all motions are contained in the microprocessor. Programmable read only memories (PROMs) are used for the fixed items, and others are placed in random access memory (RAM) by an initialization message from the central computer.

An initialization message is sent to the CCU after power turn-on or any power interruption. It is a relatively long message, about 70 bytes, but is only infrequently needed. It contains a dozen or more azimuth and elevation angle pairs including the three fixed direction values, the offset track angles, synchro zero references, deadband and hysteresis angles for each slew and slow speed motion, and maximum error angles for emergency shutdown (detrack). The local values of latitude, longitude, and time zone are included. The intent is that the PROMs be permanently programmed and that all local and operating parameters be supplied externally and be adjustable to specific and possibly time-changing needs. Local standard time, h-min-s, is sent. This sets and starts a counter whose clock time is used to compute azimuth and elevation angles for the coarse track mode. At power turn-on, after a self-activated internal initialization, the microprocessor waits for

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[2] PDC-2 is described in Reference 5.

and accepts only the external initialization message. After this is successfully received, the unit places itself in a motion-disabled state and waits for a valid command.

A precise and rigorous communication exchange protocol is used between the central computer and a CCU. Only the central unit can originate a communication event. The message consists of two sync bytes (an individual CCU address can be located here), a message length byte, message byte(s), and a check sum byte. Upon successful recognition of the second sync byte, the CCU accepts the next byte as the message length and then counts following bytes to the last expected byte, the check sum. The CCU monitors the progress of the received bytes and will time-out itself on a short, i.e., defective message. In this case, it resets itself to recognize only the first sync byte of a new message. When the expected number of bytes has been received, the CCU inhibits further reception, does the check sum comparison, and assembles and sends a standard status message back to the central unit. One of the bytes of this status message is an acknowledgment: yes if the check sums match and no if not. If no, the command byte in the original message is discarded; if yes, the new command is passed on to the control algorithm. In either case, the CCU now considers the communication event complete, releases the message receive inhibit, resets a local time-out counter, and awaits the timely arrival of the next message from the central unit. Meanwhile the central unit awaits the return status message before expiration of its time-out interval. Upon timely and successful receipt, meaning both check sum match of the return message and a yes acknowledgment byte, the central unit finally closes out the communication event as successful. If not successful for any of the several reasons, the central unit attempts to send the message twice more, and if still not successful, attempts three times to send the emergency action message, detrack. All this abnormal activity is presented in typed output form in real time in the central control area. The obvious intent is to have a continuing check on the operation of the digital communication link, to indicate that a CCU is working properly, and to take action in case of malfunction. To do this, the central unit is programmed to send a data request command at about one-minute intervals. Commands that actually change the status of the unit typically are sent infrequently and often in groups; they are placed in a queue along with the periodically entered data request commands. Any next available command in the queue is sent as soon as the preceding communication event is successfully completed. The format of the response of the CCU back to the central unit is the same for all messages including the initialization message.

The command list is presented in Table 1. The actions caused by INITIALIZATION and DATA REQUEST have been discussed previously. Commands 2 through 8 are motion commands; the concentrator moves as a result. Commands ENABLE and DISABLE provide for orderly operation both at start-up and from a safe, disabled state at a coordinate position. DETRACK RESET is the positive action required from central control acknowledging that a detrack has occurred and it now wishes to reactivate the control system at the module. In a DECODE subroutine following a message-received event, validly received commands are transferred to a control word STATRG using the code given in the table. STATRG is then passed to a MAIN subroutine for further action. The four

Table 1. Command List

Number	Command	STATRG Code
1	DETRACK RESET	01
2	OFFSET TRACK	02
3	COARSE TRACK	04
4	AUTO (FINE) TRACK	08
5	COORDINATE #1	10
6	COORDINATE #2	20
7	COORDINATE #3	40
8	DETRACK	80
9	INITIALIZATION	--
10	ENABLE	FF
11	DISABLE	00
12	DATA REQUEST	--

control words through which a command is passed in the control program are STATRG, MDREG, CTLREG, and STATW1. In MAIN, from the existing state of the concentrator as determined from the current contents of the control words, the local validity of the possibly new command in STATRG is determined. As examples, DETRACK is valid from all motion states (there was some thought of restricting it to tracking states only), DISABLE cannot be executed if the unit is in or has been commanded to a sun track mode. ENABLE can only follow DISABLE, and DETRACK RESET only DETRACK. When it is determined that STATRG is acceptable to the existing state of the unit, MDREG is set to STATRG. MDREG, of course, actually changes in content only if STATRG is a new command.

Physical control of the motion is done in two sequential subroutines, DATAQU and POSCTL. This pair is entered every 0.1 s by a system interrupt. In DATAQU the synchros are sampled, the new data compared with the old to detect motion, and offset tracking position angles computed. Synchro data are used to control all motions except AUTO TRACK which uses the sun sensors. Finally in the longest subroutine, POSCTL, the logic of the motion control is actually performed. A check for the emergency DETRACK command is made first. Then the azimuth axis is serviced followed by elevation. The output is a motor signal: do not start the motor, start it, let it run, or stop it. A final action is transfer to sun sensor control when AUTO TRACK is the commanded mode. In the general description to follow, it will be helpful to remember several things. These control sequences are entered every 0.1 s, which is a short time compared to the rate at which external things occur. Not everything is done in one cycle, e.g., a decision to stop a motor may be made in one cycle, followed by the actual stop command in the next, followed by a wait until motion stop is sensed in several more cycles. Another item is that if a motor command is in effect, repeated execution of that output produces no change; these output commands as well as most internal control actions are latched until changed. The key control word in POSCTL is CTLREG. At entry the existing CTLREG is compared with MDREG; MDREG will have been changed only if a new command is to be implemented. If different, any motion is brought to a stop and then CTLREG is changed to the new MDREG. The POSCTL subroutine is then entered in depth. A decision is reached at some point for each axis in turn. The indicated action, often do nothing (make no change), is taken, and the rest of the subroutine is skipped for that axis for that cycle. The last action, step 13, in the list below is taken after both axes have been serviced. The key items in the POSCTL cycle follow:

(1) Get commanded position value, either sun or fixed coordinate.

(2) Calculate position error; sign is direction of motion.

(3) If motor is not running, set direction; in a start/stop system, start of motion waits until deadband is exceeded.

(4) Calculate absolute value of error = abs. error.

(5) If in a track mode, check for abs. error outside detrack deadband, 0.5 deg. If yes, trouble; command DETRACK and skip out. If no, proceed.

(6) Compare abs. error with high-speed slew hysteresis, 1.0 deg. This is the distance to stop from high speed. If outside, command high speed and skip out. If inside, proceed.

(7) Check flags for stop from high speed. If at high speed and stop has not been commanded, command stop and skip out. If high-speed stop has not been completed, skip out; this will be checked again on the next cycle. If high-speed stop is completed, set flag and skip out. If high-speed stop flag is set, proceed.

(8) If command is to a coordinate position, unit has arrived there; skip out.

(9) Compare abs. error with tracking deadband; 0.3 to 0.15 deg were used. If outside, command low speed and skip out. If inside, proceed.

(10) Check low-speed stop flag. If set, go to step 12. If not set, proceed.

(11) Compare abs. error with tracking hysteresis, 0.1 deg. If outside, command low speed and skip out. If inside, command stop, set low-speed stop flag and skip out.

(12) If command is not AUTO TRACK, skip out. If command is AUTO TRACK, enable sun tracker control and skip out.

(13) After both axes have been serviced, the last item in POSCTL is the examination of flags and error terms to determine if the unit is operating in the commanded mode or is still in motion toward a new mode. If at and operating in the commanded mode, the last control word, STATW1 (status word #1 unit), is changed to CTLREG.

The contents of the four control words and the values of position, position error, and time are sent back to central control in the status return message previously described. The progress of a new command can thus be readily monitored. During a slew to a new position or mode, if STATRG, MDREG, and CTLREG all show the new mode, it indicates that the newly commanded mode has been accepted and is being implemented while STATW1 still shows the previous mode. Change of STATW1 to match the others shows arrival at the new mode.

SECTION V

PERFORMANCE AND SAFETY

The control unit was functionally checked out on the bench at JPL in Pasadena, California. No attempt at dynamic simulation was made; it was only verified that the motor control signals were proper for synchro input signals corresponding to relative positions. Site installation was uneventful. The control equipment was installed, checked, and activated in stages as the construction of the concentrator progressed. Manual drive was done first followed by computer-controlled motion to and from fixed coordinate positions, then offset track, coarse track, and finally auto track. A major problem during the latter steps was a stretch of cloudy weather that prevented quantitative evaluation of coarse track and even the use of auto (sun-controlled) track. Also somewhat troublesome was the use of borrowed PROM modification equipment. For equipment protection, certain control functions were implemented in steps to provide verification of proper operation before continuing. There were no unexpected problems, and no significant modifications were required.

The control system operated thoroughly satisfactorily although admittedly not many total operating hours were accumulated before disassembly and shipment to Albuquerque. In a truly descriptive sense, the start/stop or on/off control operation was spectacularly unspectacular. For a person standing nearby, the unit would be at rest, a motor shaft would be seen to revolve for a short time, the unit would move the required fraction of a degree shaking and vibrating somewhat, then all motion for that axis and all noise would cease until the next event, which did not occur for a definitely recognizable interval. A television camera was installed to view the location of the image of the sun relative to the generally circular structure near the focus (e.g., targets, calorimeter, etc.). Before motion, the image of the sun could be seen to have moved away from the center, and start of motion could be anticipated. During motion the TV image was jumpy. After motion the image was near the center for that axis. Each axis operated entirely independently of the other. Normal wind was not a problem; the unit was not operated when the official average wind speed at the site was above 30 mi/h. The unit did operate in the auto track mode when the speed was near 30 mi/h with occasional gusts that reached 45 mi/h. At these times there was enough wind buffetting and enough elasticity in the drive cable so that excursions beyond the sun sensor deadbands did occur. The sporadic on/off drive motions that then occurred in both directions were obviously not caused by the motion of the sun. However, the system was stable in that these motions were not continuous in time, and the unit continued to operate in the AUTO TRACK mode. After the problem of overloaded azimuth wheel bearings was recognized, the low "speed" setting was increased in steps. This provided the higher starting or breakaway torque needed to get the unit moving. However, there was no sensible change in overall pointing performance while the bearings were gradually destroyed. The COARSE TRACK mode was used at these times. It would seem that the start/stop tracking operation is extremely forgiving. Unfortunately, only a small amount of quantitative data was taken during the short operating time at the PDTS, and only very little of that can be meaningfully presented here.

One item, the AUTO TRACK motion, performed significantly better than anticipated. Modifications would have been implemented to provide a controlled, extended range for this and the PDC-2 unit. The original design intention was that the deadband for sun sensor control would be set to about 0.1 deg. Motion start would be triggered by the slowly moving edge of the image of the sun reaching this position. In practice, as soon as the unit actually moved, the image of the sun was backed away from the deadband limit and a stop signal was initiated. Due to the several electrical and mechanical time delays involved, the resultant increment of motion was only about 0.05-deg. It was not adjustable because the sun sensor signals went directly to motor control relays and no specific time delay had been provided. The smaller 0.05-deg step was certainly acceptable, and in fact made for a better optical characterization of the geometry of the reflecting surfaces. However, for ordinary service it would mean that the unit would operate twice as often as needed if the 0.1 deg from center were the real tracking requirement. The proposed modification was to bring the sun tracker signals into the microprocessor. The original concept that better redundancy was obtained by direct use was considered not to be truly valid because the microprocessor had to be operational for all tracking modes. In the microprocessor, a time delay variable in 0.1-s increments using the DATAQU and POSCTL interrupt cycle would be implemented and would be easily selectable by a software parameter change in the initialization message. In the ultimate case, once the mechanical operation of each axis had been stabilized, including correct and fixed alignment of the azimuth wheels, the delay could be set so that the unit would be returned not to the center of the deadband but to a position perhaps two-thirds of the way to the other limit. The frequency of operation of the start/stop cycle would thus be further reduced. In any case, the time delay would be readily adjustable manually and possibly automatically programmed based on actual motion of the unit to allow for changes in its mechanical characteristics.

Safety of operation is a primary requirement for the control system; on the other hand, the primary control system can only be a part of the total safety considerations of a sun-pointing, sun-focusing concentrator. The unique characteristic of these units is that there is no simple "shutdown" that is safe when they are tracking the sun and fail in one of the many possible ways. Water-cooled plates and sliding doors were not desired; the elevation axis was gravity balanced (both elevation and azimuth motions were required here anyway). Stated directly, upon failure to continue to track the sun, the requirement for equipment safety is that the unit be reliably moved off the sun with only a short delay in time and with a reasonably rapid motion. At the PDTS, nitrogen K bottles were provided and air motors were installed on the free ends of the electric motors. Because operation was always man-attended and things do not burn instantly, this was an acceptable solution for unrecoverable failure in the primary control system. An operator at the remote console could physically get to the trip valve when required. Trip was automatic for failure of 60-Hz power to the drive motor controllers. This discussion and that to follow is not intended to give a total solution to the man-unattended situation but only to present some of the aspects. Safety considerations for routine operation of this control system will be discussed first.

Protection from solar burn for routine operation was provided by the structured method of going on and off the sun. This procedure was an inherent part of the GE design and was carried essentially intact through implementation by JPL. The OFFSET TRACK mode is a full tracking mode at the rate of motion of the sun but in a direction pointing 15 deg "down" and 15 deg "east" of the sun. Establishing this offset track mode thus verifies in real time the capability of the control system to perform a tracking motion. Going to sun track is then done by the simple arithmetic removal of the 15-deg bias in two digital words. The unit then proceeds to perform a high-speed slew to the sun position along a path between the quadripod structure; ability to perform a high-speed slew and a stop from high speed has been demonstrated in the very recent past by the motion that brought the unit to offset track from a fixed coordinate position. The routine way to go off sun is the reverse of the above, i.e., insert the arithmetic biases and slew to offset track.

Protection from solar burn due to failure in the control system -- specifically in the digital, I/O, and external equipment areas and not in the electric motors, motor controllers, and various mechanical drive items -- is provided by the DETRACK motion. This motion physically is identical to going off the sun to OFFSET TRACK, viz, high speed motion in both axes "down" and "east." However, it is implemented in the hardware interface (e.g., relays, etc.) between the microprocessor and the motor controllers. The motion is stopped by an electronic time delay that was set to give about 15 deg motion. If this circuit fails, the unit drives to limit stops without harm. The hardware implementation includes the usual fail-safe techniques, failure of power supplies, open relay coils, etc. The digital program is structured to minimize and detect failures using check sums, unique digital words for commands (see STATRG table), and flag structure that requires full 8-bit match for continuing safe operation. The usual uninterruptible power supply for the microprocessor was not available at the PDTS; a DETRACK command was placed at the beginning of the local initialization cycle to which the unit would go after a fatal electrical transient. It did so on several occasions. Although not implemented at the test site, an external time-out relay that would respond to failure of the microprocessor to continue its cyclic action would be installed in a completed system. It was intended that all these malfunctions or failures would cause a DETRACK command at the hardware interface on a schedule believed to be timely enough to prevent damage.

As previously noted, unrecoverable failures in the primary control system were covered by the use of the air motors. This secondary action protected against power-line failure, motor controller failure, and electric motor failure and was considered appropriate for the controlled access and man-attended installation at the PDTS. In a man-unattended situation, not only the proper level of the ultimate protection to be provided but also the logic process of when to use it must be established. How to verify periodically that this perhaps seldom-used protection remains operable is still another and a continuing task. A last, albeit extended, comment here is that one approach is to keep these two control capabilities as separate as possible. The primary control loop can then be as simple as possible within the real-time operational requirements and engineered to have maximum reliability with the least complexity and cost. Ideally, the decision to use the secondary system comes from independent instrumentation and other sources. However, one very rational emergency signal can be generated from the digital part of the PDC-1 system. Currently in the DATAQU subroutine, it is checked if the unit is moving. This could be readily expanded to check if the unit is moving at an acceptable speed when the command is high speed. If it is not, an external signal could be provided that, together with other external logic, could be used to initiate the secondary protection motion and if appropriate, shut down the primary control system.

There are operational procedures that must be strictly obeyed for personnel and equipment safety. Whenever the control of the PDC-1 unit is from a remote station (computer or remote manual) there is the possibility of a DETRACK action. At these times, people and equipment must be prohibited from entry into the region of motion. Because the primary work carried out at the JPL Edwards Test Station has been hazardous chemical rocket propulsion testing, very strict and time-tested procedures already existed; test site status is rigorously controlled by a green/amber/red color light indication. Once concentrator control is transferred to remote, the site status becomes red; no person or thing is allowed into the motion region. However, it was deemed safe for knowledgeable people at the PDTS to approach the concentrator under red status for such things as observation and control system adjustment or return of control to the local site. These can be done without entering the motion region. However, for people or equipment to enter the motion area, it is mandatory to return and maintain control at the immediate site. The master control transfer switches are located on the side of the azimuth platform, outside the motion region, and readily accessible from ground level. The local electrical disconnect switches for the drive motors and conventional push-button-type controls are also located at this place. For extensive work on the unit and overnight or extended non-operational storage, these local electrical disconnects are tripped, and the elevation and azimuth axes are mechanically secured. For minor adjustments, it was deemed safe to move the unit at low speeds from this local station with people and equipment in the extended path of motion; immediate and positive electrical shutdown could be done. The preceding discussion has dealt only with safe operation of the primary control system. Similar, strictly enforced procedures are absolutely required for any secondary motion capability. It must be positively taken off line for human or materiel entry and likewise positively restored with a suitable interlock with the primary system when sun tracking is to be done.

An operational incident is noted here because of its applicability to man-unattended operation. On one occasion in mid-morning the unit was moved from its down and north overnight storage location to an intermediate horizontal and east position, then to OFFSET TRACK, and finally to a sun-tracking mode where it operated on-sun for several hours. When commanded to return to OFFSET TRACK, it moved downward but did not move in the eastward direction in azimuth because of a faulty limit switch probably caused by prolonged moisture entry. At this point the operator returned the unit to manual control and drove farther west, which removed the image of the sun from one of the quadripod legs. Note that all the previous azimuth motions had been westward. Three investigative statements follow. At no time was there any danger whatsoever to personnel. No equipment damage occurred because the operator took available, appropriate, and timely action. Lastly, although the malfunction quite likely existed at the start of this operation and would have been detected by a DETRACK check or any attempt to move eastward, there is no guarantee that it did not occur or could not have occurred after such a procedural test. Several conclusions and actions are indicated. Confirming a previous remark, there definitely is no simple safe shutdown of this type of sun-focusing equipment; the unit must be moved to the safe position. Secondly, in addition to checking the ability to move in all directions before operation on sun, equipment to monitor this ability while the unit is in normal operation would have been installed. Measurement of the continuing presence of control voltages after the limit switches using four spare input channels would have been a very straightforward task. Lastly, providing equipment-safe, man-unattended operation is a major task. For such man-unattended operation, it is suggested that it will be necessary to assign a location in a failure tree below which equipment protection action will be provided and above which damage to the equipment will be accepted. That this will be necessary should be formally recognized by the project close to project start so that concerted and forward-moving design and implementation action can follow. Many protection features and check procedures can be incorporated into a design without compromising the reliability of the ordinary operation or increasing costs prohibitively. However, at some point -- for the PDC-1 design it includes wheel or cable failure -- there is probably no protective action that is practical or maybe even possible. Vandalism at a man-unattended site is another part of this overall problem that cannot be ignored. (Results of a general study of solar walk-off protection are given in Reference 6.)

A considerable amount of detail has been presented in this report, much of which cannot be readily summarized, hence the concluding statement will be short and direct. A start/stop solar concentrator control system was built and performed to and beyond specifications that were consistent with the optical capabilities of the unit. For tracking requirements more stringent than the achieved 0.05-deg deadband, at some point the start/stop system must be replaced by a continuous tracking system.

SECTION VI

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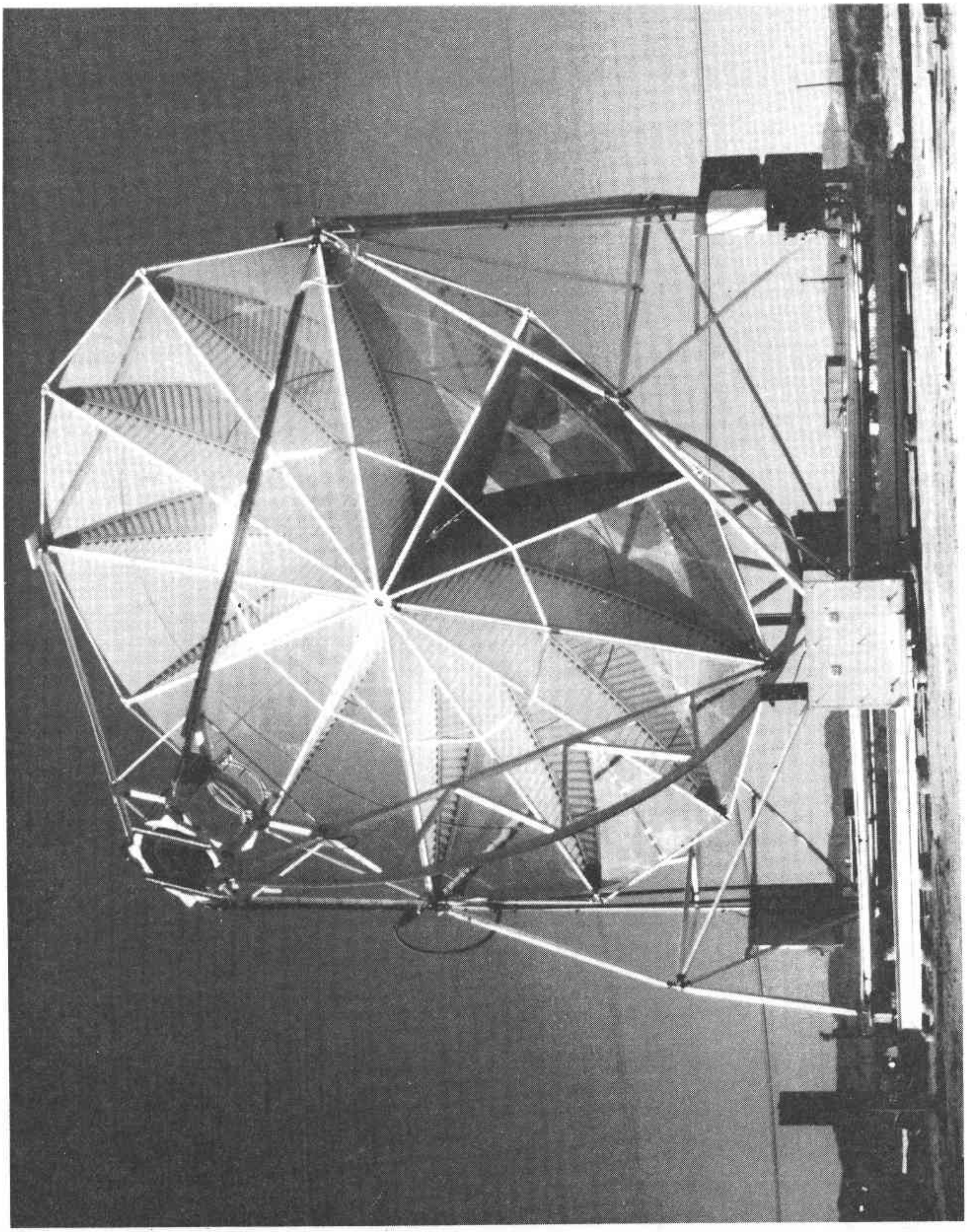

Figure 1. General View of PDC-1

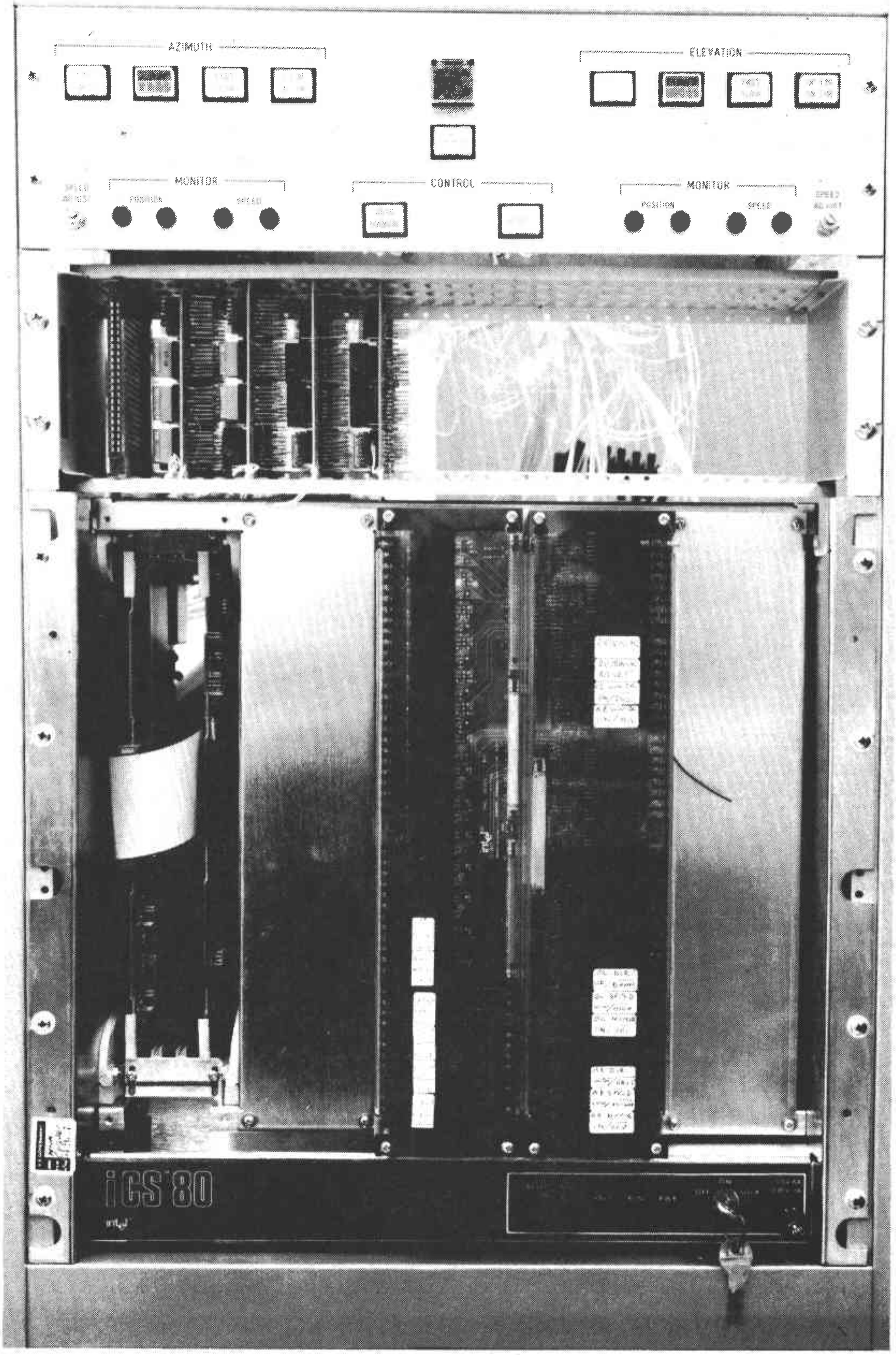

Figure 2. Concentrator Control Unit (CCU)

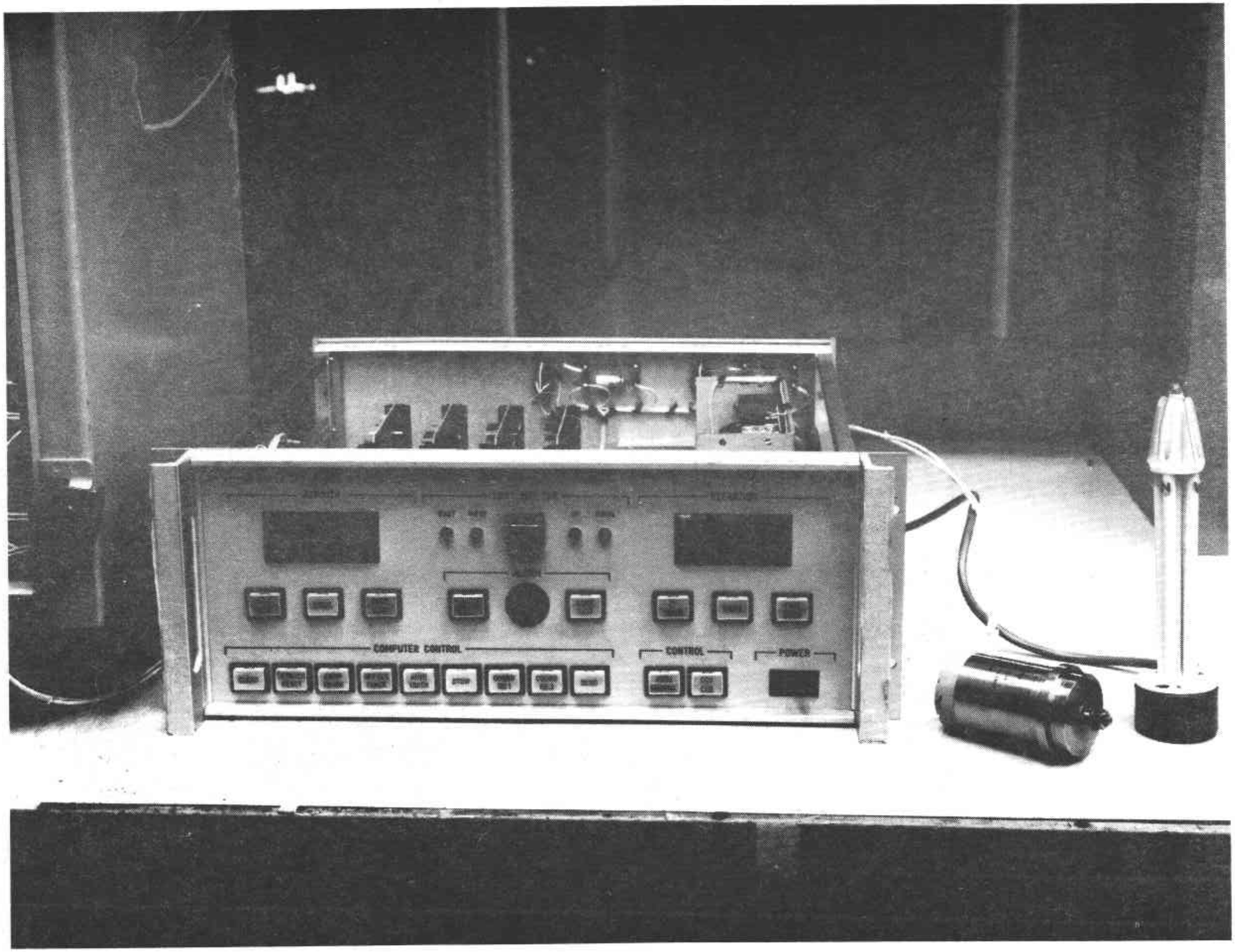

Figure 3. Remote Control Unit (CCR), Synchro, and Sun Sensor

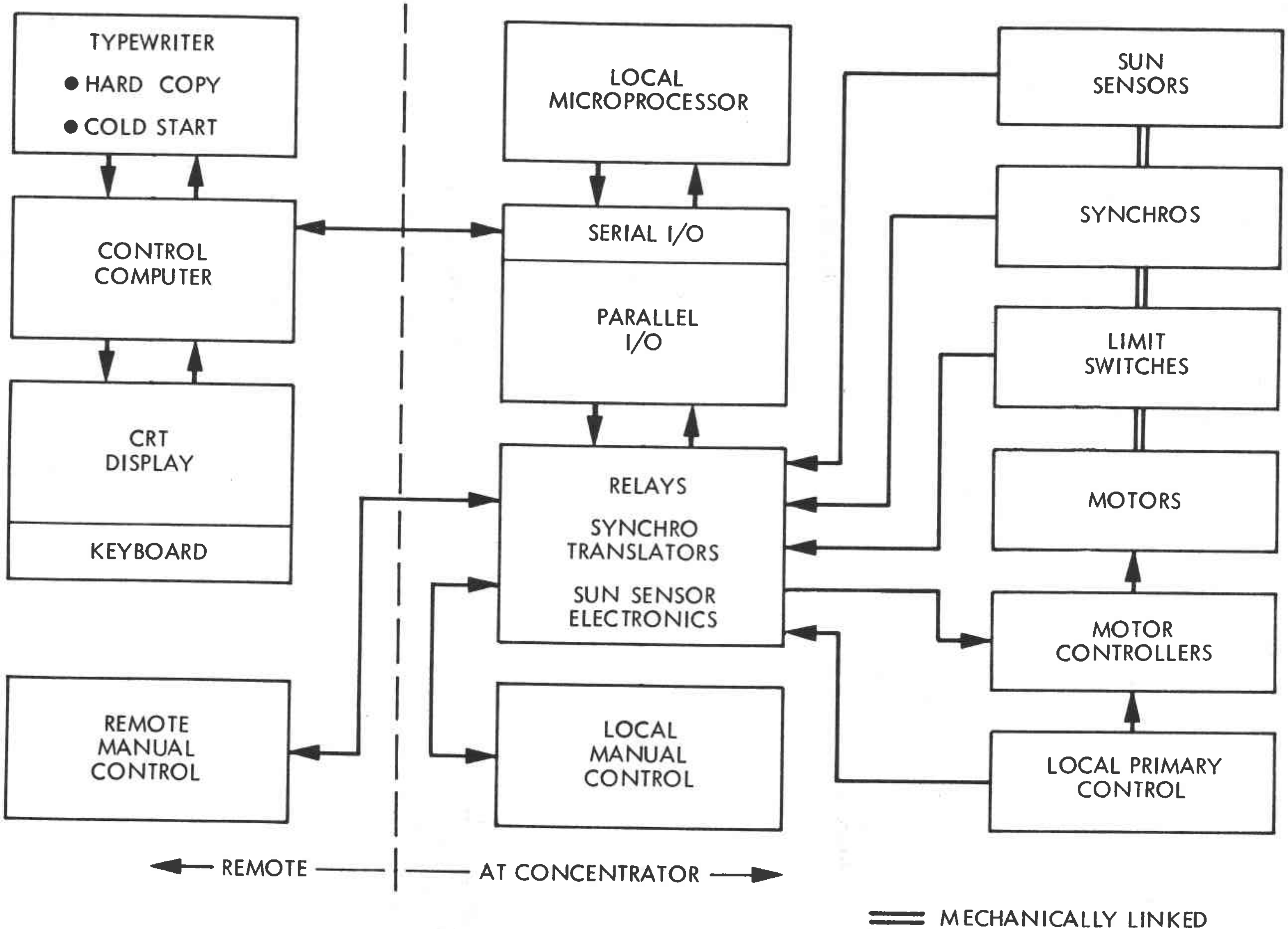

Figure 4. System Block Diagram

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