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Optical Links in the Angle-Data Assembly of the 70-Meter Antennas

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In the precision-pointing mode the 70-meter antennas utilize an optical link provided by an autocollimator. In an effort to improve reliability and performance, commercial instruments have been evaluated as replacement candidates, and upgraded versions of the existing instruments have been designed and tested. The latter have been selected for the Neptune encounter, but commercial instruments with digital output show promise of significant performance improvement for the post-encounter period.

I. Introduction

When the 70-meter antennas of the Deep Space Network are operated in the precision-pointing mode, an optical link provided by an autocollimator plays an important role in the measurement of pointing angles. Over the past several years there has been an effort to upgrade both the reliability and the performance of the precision-pointing mode by upgrading or replacing the instrumentation which provides this link. Section II reviews the rationale for the use of a pointing subsystem requiring an optical link and describes the elements of the subsystem. Section III discusses the general technology of autocollimators and the parameters used to characterize them. It then describes and compares detection techniques used in commercial autocollimators. Section IV reports on the evaluation of several commercial instruments. Most of these evaluations are the result of testing in the JPL autocollimator facility. Section V describes development work done at JPL in the areas of improvements to the present autocollimators and the interfacing of an autocollimator with a digital output to the antenna control system. Section VI summarizes the present situation and makes recommendations concerning the autocollimators both for the near term and for the period after Neptune encounter.

II. Rationale for the Optical Link in Antenna Pointing

The 70-meter antennas, like most large antennas, are in altitude-over-azimuth mounts. In the ideal situation an alidade structure rotates about an axis perfectly aligned with the local vertical and supports a perfectly horizontal axis about which the tipping structure rotates carrying the dish, subreflector, feed, etc. In this ideal situation it is only necessary to translate the astronomical coordinates, declination and hour angle, into azimuth and elevation in order to point the antenna. In actual practice the situation is far from ideal. Foundations may settle, moving the azimuthal axis off the vertical and giving a tilt to the elevation axis which depends upon the azimuthal angle. In addition, solar heating, aerodynamic forces, and gravitational loading will distort the structure, introducing pointing errors.

There are two general approaches to dealing with the situation. One is to measure rotation about the azimuth and elevation axes with shaft encoders and depend upon mathematical modeling both for the correction of systematic errors and disturbances and for the transformation to declination and hour angle. The other approach is to utilize a separate pointing-metrology system which is designed to be less susceptible to errors and disturbances than the antenna and which determines the pointing direction of the antenna. Such a pointing-metrology system can range in complexity from one which surveys many points on the dish, subreflector, and feed and solves for the instantaneous pointing direction to one which determines a single reference direction on the tipping structure. Neither approach can completely eliminate the need for modeling, but they can reduce the number of parameters which must be modeled. The present system for the 70-meter antennas determines a single direction, that of the normal to the intermediate reference structure located on the center line of the dish between the vertex of the dish and the elevation axis.

There are five major elements in a pointing-metrology system of the latter type: a mechanical support structure that is as independent of the rest of the antenna structure as possible; an element articulated about two axes which establishes the pointing direction; encoders to determine the pointing direction of the articulated element; a link to the reference element on the antenna; and an enclosure to minimize environmental disturbances. In principle the link could be provided in a number of ways. In practice there are strong reasons for making it an optical one. The chief reason is disturbance isolation. By its nature an optical link is unidirectional and, in the appropriate configuration, isolates the articulated element from disturbances to the antenna, particularly vibration. By using an optical link as opposed to a mechanical one it is possible to have independent motion of the antenna and the articulated element. This facilitates slewing and allows for operation in a lower-precision mode with elevation and azimuth encoders, should the precision mode be inoperative. A light beam is weightless and can, with proper design of the instrumentation, transfer a pointing direction free from errors caused by gravity deflections. Finally, the techniques for providing the instrumentation are well established with substantial field experience in a variety of applications.

A metrology system, such as described above, may be configured to operate in two distinctly different ways. The articulated element of the metrology system may be pointed in the desired direction with its encoders and the link used to generate a control signal for the antenna, causing it to follow the articulated element. Alternatively, the link may be used to drive the articulated element to follow the antenna. The encoders of the metrology system then give the present point direction of the antenna. The pointing-metrology system of the 70-meter antennas is used in the first of these two modes although much of the hardware needed for the second mode is in place.

The actual configuration for the pointing metrology system of the 70-meter antennas, shown schematically in Fig. 1, is the following: A central support column rises from the foundation along the azimuthal axis to a point a few feet below the elevation axis. The articulated structure is in an equatorial-fork mount similar to those used for telescopes and supports a plane mirror. The pointing direction of the metrology system is the normal to the plane mirror. Its angular position in declination and hour angle is measured by an Inductosyn transducer on each axis. The pointing direction is transferred to the intermediate reference structure by an optical link provided by an autocollimator. The autocollimator projects a beam of light onto the plane mirror and develops an electrical output signal proportional to the angular offset of the returned beam. These signals are developed for rotating about the elevation axis and a direction orthogonal to it (cross elevation) and serve as the control signals for pointing in elevation and azimuth. The signal flow is shown in Fig. 2. The critical nature of the optical link is evident and the following sections discuss its implementation in detail.

III. Autocollimator Technology

A. General Characteristics

A general autocollimator configuration is shown in Fig. 3. Light emitted from a source at the focus of a lens is reflected by a beam splitter and formed into a parallel beam by the lens. This beam is returned by the mirror whose rotation is being measured and is focused by the lens on a position-detection element. When the mirror is precisely perpendicular to the axis of the lens, the returned spot is centered on the element. As the mirror is rotated the spot is moved on the element. This generates a signal proportional to the linear displacement of the spot which for the small angles involved is proportional to the mirror rotation. The angular coverage at zero working distance is determined by the ratio of the field-stop size to the focal length of the objective lens. As the working distance increases, a given angular deflection of the mirror causes more of the return beam to miss the entrance aperture of the lens. This results in a decrease in signal which limits performance.

B. Parameters

Several parameters are required to characterize an autocollimator. Some of these can be represented on the transfer curve shown schematically in Fig. 4, which plots the electrical output as a function of angular offset. Of particular importance for control functions are those parameters relating to the central part of the curve: the slope, the linearity, and the offset at null. The other parameters, the linear range and the acquisition range, are of importance for initial alignment but do not figure in the performance once a control loop has been closed. Other parameters of importance not shown on the curve are maximum working distance, noise-equivalent angle, electrical phase shift, cross-coupling, and all-attitude sensitivity. Table 1 gives the specified values for these parameters for the DSN autocollimators.

The maximum working distance and the noise-equivalent angle (NEA) are very closely connected. At the working distances encountered in the antenna installation the NEA is determined primarily by air turbulence and not by the intrinsic instrument characteristics. At very short working distances the converse is true and the NEA is determined by the instrument characteristics. The electrical phase shift is a measure of the response to a moving mirror. It must be traded off against instrumental NEA. The cross-coupling is a measure of the degree to which an angular offset about one mirror axis produces a spurious output for the other axis. All-attitude sensitivity is a measure of spurious outputs produced by tipping the instrument in a gravitational field.

C. Description of Detection Techniques

The selection of the technique for detecting the position of the returned spot in the focal plane is a critical design decision, and a number of techniques have been used in commercial instruments over the years. Figures 5 and 6 show the techniques used in instruments tested in this study. Figure 5 shows mechanical scanning of the image of the source aperture over the detector field of view. There are many ways in which this can be done both in terms of the shapes of the source and detector apertures and in terms of the scan pattern. The particular one shown is used in the Kollmorgen-built instruments currently being used on the antennas. A rotating optical element nutates the image of the source aperture on the detector aperture. In the nutational motion the center of the image travels in a circle, but the image does not rotate. When the returned beam is in the null position this circular motion is centered on the detector aperture and the detector output has zero first-harmonic content. As the image is displaced from the center of the detector, the first harmonic of the detector output increases. The phase of this signal indicates the direction of displacement. Since the signals for each axis are in quadrature they can readily be separated by phase-sensitive rectification. The square source aperture generates a strong fourth harmonic in the detector output, but this is removed by the filtering which follows the phase-sensitive rectification.

Figure 6 shows four detecting techniques which do not involve mechanical scanning. In the interest of clarity all configurations are shown for a single axis of motion. All are adaptable to two-axis operation but not with equal facility. The dual source has been widely used in a variety of implementations for many years. The sources are half-wave modulated 180 degrees out of phase, and synchronous rectification of the ac component of the detector output is used to develop the output signal. Davidson Optronics has used this technique for a number of years in their line of autocollimators. They use gas-discharge lamps as the light source and implement two-axis operation by using two wavelength regions: one obtained from mercury-vapor lamps, and the other provided by neon lamps.

The dual source has also been used by Micro-Radian for several years in their line but in a different implementation [1]. They use two extended-area light emitting diodes (LEDs) and avoid the light losses inherent in a beam splitter by placing the detector behind the gap between the sources. Since this arrangement does not lend itself to two-axis operation with a single optical system, Micro-Radian uses two separate optical systems mounted close together. Cross talk is avoided by using a different modulation frequency for each axis.

The split detector is used in a variety of optical sensing systems including autocollimators and is commonly constructed by placing two silicon photodetectors on a single substrate. The outputs of the two detectors are combined as $(A - B)/(A + B)$ to yield the position-sensitive signal. Generally the dc processing is used. Unlike the dual source, the dual detector is readily extended to two-axis operation by dividing the detector into quadrants and processing the signals as $(A + B - C - D)/(A + B + C + D)$ for one axis and $(A + B + C - D)/(A + B + C + D)$ for the other axis.

Lateral-effect photodetectors are an alternative use of silicon-detector technology. The detectors are produced by diffusing a P-type dopant and an N-type dopant into opposite sides of intrinsic silicon base material. Two contacts, one at each end of the sensor, provide alternative paths for the photocurrent, and the division of the current between the two contacts is a measure of the location of the spot of light on the detector. Linearity is fairly good over the central 25 percent of the area and the total range can be quite large [2]. Like the dual detector the processing is $(A - B/A + B)$, and extension to two axes is accomplished by adding a second set of contacts.

The linear-array CCD (charge coupled device) is significantly different from the other devices of Fig. 6 in that it involves discrete pixels read out sequentially. Typically the source aperture is made in the form of a slit so that motion in the direction perpendicular to the array will not cause loss of signal. The slit image is made wide enough to spread the light over several pixels for accurate centroid determination.

D. Comparison of Detection Techniques

A mechanical scanning system can, if carefully designed and constructed, yield high quality performance. The accuracy of the scanning motion must be high, and the sensitivity of the detector and illumination of the source aperture must be very uniform. Since there are practical upper limits to the angular speed of the scanning element, the modulation frequency is limited to the 100 to 200 Hz range. The filtering required after the synchronous rectification in this frequency range limits the signal bandwidth for some applications. The use of mechanical scanning also imposes an operational limitation because of the finite bearing lifetime.

The dual source technique also requires good uniformity of illumination over the source apertures. In addition the source must have good modulation characteristics. In practice this also means sources of low brightness if a reasonable level of system complexity is to be maintained. The gas discharge lamps used by Davidson Optronics for this purpose have only a few hundred hours of life. The LEDs used by Micro-Radian have very long life but low brightness. This limits their application to single-axis instruments and modest working distances.

The dual or quadrant detector provides a high-accuracy system over a limited angular range. Again, source uniformity is important. If a substantial linear range is required the source must be of large lateral extent as well as very uniform. If the linear range is limited but a large acquisition range is required, this detector is very good. Since the zero position is marked by the physical divisions of the detector surface, the device lends itself to systems requiring a well-defined zero.

In contrast, the lateral-effect photodiode can be used with a concentrated source which need not be particularly uniform since charge is integrated over the entire source image. An additional advantage of the lateral-effect photodiode is that it intrinsically has a large acquisition range. Disadvantages are that the central region over which the behavior may be considered linear is very limited and there is no physical identification of the axis point as there is in a divided detector. General indications are that the best linearity is obtained with single-axis units. For example, data sheets from SiTek Laboratories (Sweden) show typical nonlinearities of ±0.1 percent for single-axis units and ±0.5 percent for two-axis units.

The linear CCD has the great advantage that the pixels are fixed in the detector and are in one-to-one correspondence to the angular offset of the returned beam. If pixels are displaced from the ideal location as a result of manufacturing errors, a one-time calibration is sufficient to correct for this. As has already been indicated, it is desirable to spread the image of the source aperture over several pixels in order to obtain a better centroid of the image. A simple approach is a small amount of defocus. If done correctly the centroid can be determined to one-twentieth of a pixel. Since the pixels must be read individually and the resulting signals processed to obtain the centroid, there is an intrinsic delay in the output. This may be significant for applications requiring higher bandwidths and is the chief drawback to the use of CCD detectors in this application.

IV. Evaluation of Commercial Autocollimators

In an effort to find a replacement for the Kollmorgen-built instruments a number of commercially available autocollimators were evaluated. Most were evaluated in the autocollimator test facility at JPL. In two instances the manufacturer's facility was visited, and for all instruments there were detailed technical discussions with the vendor or his representatives. The evaluation criteria were whether the instrument (1) could meet the present specification (Table 1); (2) could meet the optical, electrical, and mechanical interface requirements on the antenna; and (3) would be easy to maintain.

In considering the requirements, only the interface constraints of the intermediate reference structure were taken into account, and the question of operation from the master equatorial was not addressed. This limitation on the scope of the study was adopted because all autocollimators investigated were packaged as an optical head connected to a separate electronics box and were of sizes and shapes which precluded installation on the master equatorial without extensive re-engineering.

In the following discussion autocollimators are grouped by manufacturer. There is no particular significance to the order in which they are discussed.

A. Davidson Optronics

The optical head of the Davidson instrument, model D-696, is physically large. The optical head is approximately 280 × 230 × 203 mm (11 × 9 × 8 inches) with a lens aperture of 50.8 mm (2 inches) and a lens barrel diameter of 72.7202 mm (2.863 inches). The electronic unit is 610 × 405 × 255 mm (24 × 16 × 10 inches). It has been in use for many years and is a standard for a number of military applications. The instrument, as was discussed above, uses gas-discharge tubes with a relatively short life. This factor, together with the large physical size and attendant mounting difficulties, led to a decision not to test this instrument.

B. Micro-Radian

Micro-Radian has offered a temperature-compensated instrument based on single-axis optical heads 203 mm (8 inches) long and 50.8 mm (2 inches) in diameter for a number of years. The lens aperture is 25.4 mm (1 inch) and the barrel is 38.1 mm (1.5 inches) in diameter. For two-axis operation, model 145D, two optical heads are mounted side by side and connected to a single electronics unit of approximate dimension 305 X 230 X 155 mm (12 X 9 X 6 inches). Since the dual-axis instrument uses single-axis optical heads, only single-axis instruments were evaluated. Two examples of the single-axis instrument, both model 150, were extensively tested in the JPL facility, although not all tests were performed on both instruments. Transfer curves were measured at various working distances; cross-coupling and NEA were measured; all-attitude sensitivity was checked; and phase shift was measured. Both instruments showed good transfer-curve characteristics at shorter working distances but did not meet requirements at 2.4 m. One instrument showed acceptable linearity at about 1.8 m but did not return enough signal at 2.4 m. The other instrument would operate at 2.4 m but did not meet the linearity specifications in the vicinity of zero.

The phase shift tests were made with a variable-frequency oscillating mirror and were carried out at various settings of the bandwidth control. It was found that at 300 Hz bandwidth the phase shift at 5 Hz was negligible. At 100 Hz bandwidth the phase shift at 5 Hz was approximately 10 degrees.

The double-barreled construction of the optical head used by Micro-Radian prevents it from being a direct substitution for the Kollmorgen 874 currently being used on the antennas, and some modification of the optical assembly on the intermediate reference structure would be required. The simplest modification would be to increase the size of the reflector closest to the autocollimator to accommodate both beams. The most elaborate modification would be to extend the intermediate reference structure, bringing the optical assembly much closer to the master equatorial, and to mount the instrument in looking directly at the master-equatorial mirror, thus minimizing the number of reflections. If such extensive modifications were made, the successful operation of the Micro-Radian instrument could be predicted with a high level of confidence. If, on the other hand, the optical assembly were modified only the minimum amount, the working distance would remain large and the four relay reflections would remain in the optical path. Since the test results indicate marginal performance under these conditions, the Micro-Radian instrument was dropped from further consideration.

C. United Detector Technology

For a number of years UDT has offered a line of position sensors based on quadrant detectors and lateral-effect photodiodes. The line consists of a variety of optical heads for different applications and a number of alternative electronic units for signal processing and data output. The first autocollimator in this line was the model 1000 and was a modular unit with interchangeable lenses and detectors. It was tested for this application with both types of detectors and with both the 200 and 400 mm focal length lenses. The results of the tests were promising but there were shortcomings. Chief among these was the modular construction with joints which would not provide the required long-term mechanical stability. In addition, the best performance was obtained with the 400 mm lens which had an 88.9 mm (3.5 inch) barrel diameter and a 69.85 mm (2.75 inch) aperture. This presented problems with both the optical and mechanical interfaces.

Some time after the completion of the above tests a model 1010 was introduced. The optical head for this was a non-modular, compact unit with a lens barrel of 38.1 mm (1.5 inches) and a 25.4 mm (1 inch) aperture. The small size of this configuration removed the optical and mechanical interface problems, and the one-piece construction removed the potential problems with the modular approach. As soon as an instrument became available it was tested extensively. The results were extremely poor in terms of sensitivity, stability, and NEA. These results were reported to the manufacturer, who undertook an investigation of the manufacturing process. It was finally determined that an incorrectly specified beam splitter had been used in the first batch of instruments.

An instrument with the correct beam splitter was subsequently obtained and tested. At a working distance of 2.1 m (84 inches) one axis could be measured and gave reasonable results. The other axis, however, did not yield useful output. This was traced to poor alignment of the illumination from the LED source with the optical axis of the instrument. A third instrument was obtained and showed the same problem. For this instrument the misalignment was measured to be approximately three-quarters of a degree.

The conclusions were that the model 1010 could only be used if the working distance could be reduced and if the manufacturer were able to improve the alignment of the illumination with the optical axis. The question of thermal sensitivity was not addressed. Even if the other difficulties could be overcome, this would remain a potential problem.

D. Möller-Wedel

The Möller-Wedel autocollimator (J.D. Möller Optische Werk GmbH, West Germany) came on the market late in this study. Its optical head has a 65 mm (2.559 inches) lens barrel and an aperture of 50 mm. The overall dimensions of the head are approximately 380 × 203 × 127 mm. Fairchild 1728 pixel linear CCD array detectors are used for each axis. The centroids are calculated by a combination of analog and digital processing and output digitally on an RS-232 port.

Since the instrument has a digital output it was necessary to design and build an interface unit to meet the electrical interface requirements for analog signals. To allow time for this, the instrument was leased for an extended period rather than borrowed for a single test. The interface unit receives the digital data stream from the autocollimator, separates the data for the two axes, and converts it into two analog voltages of appropriate size. The interface unit is described in more detail in Section V.

First tests indicated that the instrument was extremely precise, had adequate working distance, and generally met all specifications with ample margins, except all-attitude sensitivity and speed of response, which in the original configuration was much too slow. These points were discussed with Wilhelm Duis, the cognizant engineer from Möller-Wedel, during a visit to JPL. He proposed two modifications: (1) a stiffening collar at the junction of the lens barrel and the body of the optical head; and (2) a high-speed data mode in which there was no averaging of successive centroids and no use of the stored calibration. With these modifications the all-attitude specification of three arc seconds peak to peak was met and the data rate raised to 100 readings per second. The removal of the averaging and stored-calibration routines had an insignificant effect on the performance for this application. The linearity remained excellent and the NEA was acceptable.

Since there is a fixed processing and communication delay, the time constant was chosen rather than the phase shift as being a better representation of the instrument characteristics. This measurement was made by introducing a step change in the minor angle and photographing the analog output from the interface unit on an oscilloscope. The time constant was measured to be 0.0134 sec. If a simple RC filter is assumed, this corresponds to a phase shift of 23 degrees at 5 Hz.

Since the decision was made to purchase the instrument and incorporate it into the autocollimator test facility, and since other options presented fewer interface problems, it was decided to defer further work with the Möller-Wedel instrument as a replacement for the Kollmorgen 874. The work of preparing the required interface electronics was completed and will be described in the next section.

V. Development Work at JPL

In addition to the maintenance of the Kollmorgen instruments and the testing of commercial instruments, three developments have been carried out at JPL. They are (1) the improvement of the Kollmorgen 874 without changing its working principle; (2) the replacement of the scanning system of the Kollmorgen instrument by an array detector without changing the optical or mechanical configuration or the electrical interface; and (3) the construction of an interface for the Möller-Wedel. The motivation for these specific tasks was preparation for the Neptune encounter, and their scheduling and the level of effort were strongly influenced by this fact. Accordingly, development was undertaken in parallel with the plan of dropping the less promising approaches at the appropriate time.

A. Improvements to the Kollmorgen 874

The improvements undertaken in this task leave the basic operating principle of the model 874 unchanged. It remains a mechanically scanned system. The major improvements are in the areas of illumination, mechanical reliability, and circuit stability.

The original design of the model 874 utilized a separately mounted lamphouse connected to the instrument by a bundle of optical fibers. The design depended on the random arrangement of fibers in the bundle to assure uniform illumination over the source aperture. This often resulted in unsatisfactory source uniformity, changes in illumination and the attendant zero shift when the fiber bundle was moved, and problems with damaged fibers. To overcome these problems, a new lamphouse was designed keeping the same transformer and lamp but mounting directly to the instrument housing. The flexible fiber bundle was replaced with a rigid light pipe, and the diffuser directly behind the aperture was improved by shaping the side toward the incident light into a lens. These changes resulted in a significant improvement in light-source performance.

The mechanical scanning in the model 874 is provided by a nutation plate rotating at 9000 rpm. The motor which drives it must operate at approximately 5600 rpm, and motor life has long been a problem. One of the modifications was to install a longer-lived, higher-torque motor. This entailed a new motor mount and an adjustment of the supply voltage.

The approach to the problems of light source variations and the variation of returned flux with distance constitutes a significant part of autocollimator design. The approach used in model 874 is that of automatic gain control. The level of the direct current from the detector is used to control the gain of the ac amplification to keep the sensitivity to angular variations (slope of the transfer curve) constant. The experience with the AGC of the 874 has been quite varied. For some units the AGC works well and a constant output can be maintained for wide variations in the flux on the detector. For other units there have been problems with excessive phase shift and instabilities if the circuit is adjusted for good AGC operation.

Since the Mark IVA firmware can accommodate changes in the slope of the transfer curve and since the transfer curve slope can be measured in the field by fixing either the antenna or the master equatorial and scanning the other, it was decided to replace the AGC circuit with a simple gain control. Under this approach the instruments are shipped out with a gain setting which gives the specified slope to the transfer curve at 2.44 m working distance in the laboratory environment. When the instrument is installed for the antenna, the gain is measured and entered into the control computer, and this gain is checked from time to time as required.

The changes outlined here as well as some other minor circuit improvements are being implemented in instruments as they come in for routine repair and recalibration.

B. Replacement of Scanning System by a Circular Detector Array

To this point the only options that have been discussed have been upgrading the model 874 without changing the operating principle or replacing it completely with a commercial instrument. A third option is also being pursued: that of keeping the optical and mechanical configuration of the 874 intact but replacing the scanning system with an array detector. This has the considerable advantage of leaving the optical and mechanical interfaces unchanged. The approach had been under consideration for several years, but lack of a suitable detector had blocked progress. When the Parkes Radio Astronomy Observatory in Australia reported good results with a Reticon RO-64 circular array detector, it was decided to investigate its use in the model 874. The chief issues were those of sufficient photometric response and sensitivity to variations in illumination across the source aperture. Promising results from simulation studies and laboratory test led to a prototype test on DSS-14 in September 1987. Except for a minor problem with the acquisition indicator, the performance was satisfactory during a month of testing. The decision was made to proceed with an engineering model, which is now under construction.

The operating principle of the modified instrument (designated 874-64) is very similar to that of the original model 874 except that the scanning of the array has replaced the mechanical scanning. The RO-64 detector consists of 64 silicon photodiodes in a circular array 2 mm in diameter. In response to a clock signal the elements are read out continuously in sequence. This has an advantage, in addition to the quite obvious elimination of mechanical scanning, in that each of the 64 elements integrates continuously over the time interval between readouts. As a consequence, signal-to-noise ratios are greatly improved over those of a scanning system of comparable resolution. Furthermore, scanning rates may be much higher than for mechanical systems, resulting in higher bandwidth systems. A circular source aperture is used, and the image on the detector is slightly defocused to produce tapering illumination at the edge of the image. When the image is centered on the array, all pixels in the array give the same signal. As the center of the image moves in a particular direction, the signals from the pixels toward which the image is moving increase and those diametrically opposite decrease.

The block diagram for the electronics is shown in Fig. 7. The clock, counters, and dividers generate the clocking signals for the circular array and the reference signals for the demodulator. A synchronizing signal generated by the array on the completion of each scan synchronizes the demodulation signals with position on the array and enables the demodulators to output signals corresponding to designated X and Y directions. A by-product of this is that it is possible to electronically "rotate" the array to place the axes in the desired directions. The signal from the detector consists of a train of pulses at a constant repetition rate amplitude modulated by the variation of the light intensity around the array. Although the functions are not in fact sequential, the demodulation and filter circuits may be thought of as performing three functions: (1) detecting the low frequency modulation on the pulse train; (2) synchronously rectifying this modulation in each of two channels; and (3) filtering the rectified signal to produce dc signals proportional to the offset.

The model 874-64 is able to meet the specifications in all areas except possibly acquisition range. However, such a large acquisition range is not required operationally. The phase shift at 5 Hz is well below the specified values. It was estimated to be 0.2 degree, which is at the limit of what can be measured.

C. Möller-Wedel Interface

It has already been mentioned that it was necessary to construct an interface unit to permit the Möller-Wedel autocollimator to be used as a replacement for the Kollmorgen 874. The instrument as modified for this particular application had two data modes at the RS-232 port: a normal mode using 2400 baud ASCII characters and a high-speed rate, 9600 baud absolute binary. It is the high-speed rate that must be processed for control applications. The basic operation in the interface unit consists of reading the digital output of the Möller-Wedel, applying zero-point and scale-factor corrections, converting to analog voltages, and outputting the properly scaled voltage for each axis. In addition the unit must test for good data and close an acquisition relay when valid data is being processed.

The interface unit is built around a 990/101M computer based on Texas Instruments' TMS9900 16 bit microprocessor. It has four kilobytes of RAM, four kilobytes of PROM, two kilobytes of non-volatile CMOS memory (battery backup), and two RS-232 ports. The D/A converters are memory mapped I/O ports and are followed by gain stages to achieve the required 64 V/degree sensitivity. Both the Möller-Wedel and the interface unit operate from the 60 Hz line, but power is switched by the 400 Hz line that operates the 874 autocollimators. It was necessary to make a small modification to the Möller-Wedel to make it power up in the high-speed data mode. With these modifications, the Möller-Wedel will resemble the 874 in all operational aspects.

There are three programmed modes of operation for the interface unit. They differ in the values taken for the scale zero. The first program uses the factory calibrated zero. The second takes the first value read and calls that "zero." The third program uses the constants stored by the second program for all subsequent measurements, and is the one used for the normal control function.

In mounting the Möller-Wedel autocollimator on the antenna the optical head would mount in place of the 874. The electronics box would be mounted close to it on the IRS. The interface unit would be on the floor of the master-equatorial room and would connect to the junction box on the wall of the room rather than to the one on the IRS.

VI. Summary and Recommendations

A number of commercial autocollimators have been evaluated. Based on the assumption that modifications to the intermediate reference structure would be minimal, no instruments with analog output were judged satisfactory as a replacement for the Kollmorgen 874. A digital instrument made by Möller-Wedel, after factory modification, showed sufficient promise that an interface unit was designed and built. It has not been tested on the antenna because other solutions developed in parallel offered promise of simpler solutions for the Voyager Neptune encounter period.

For the Neptune encounter a two-step approach has been taken to the upgrading of the Kollmorgen 874. The first step seeks to improve the reliability without changing the basic technology of the instrument. The changes include a new illumination system, a new motor, and the replacement of the AGC circuit with a manual gain control. These changes are being implemented as instruments come in for routine maintenance and recalibration. The second step involves the more significant change of replacing the mechanical scanning with a circular array detector. A prototype has been tested at DSS-14, and an engineering model is now under construction. Following its testing the decision will be made concerning the conversion of other units.

For the period after the Neptune encounter, careful consideration should be given to digital-output instruments. Möller-Wedel has under development a high-speed, single-axis autocollimator with parallel digital output. It uses a high-intensity LED and operates at a 400 Hz update rate. The evaluation of this instrument is strongly recommended.

References

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Table 1. Principal specifications for the autocollimator for the 70-meter antennas

Slope of the transfer curve (V/degree)	64
Linear range (arc seconds)	±300
Linearity (percent)	±10
Accuracy at null (arc seconds)	±1
Acquisition range (arc minutes)	±23
Maximum working distance (meters)	2.44
RMS noise-equivalent angle (arc seconds)	0.5
Maximum phase shift 0–5 Hz (degrees)	5
Cross-coupling (percent)	±2
All-attitude sensitivity (peak to peak, arc seconds)	3

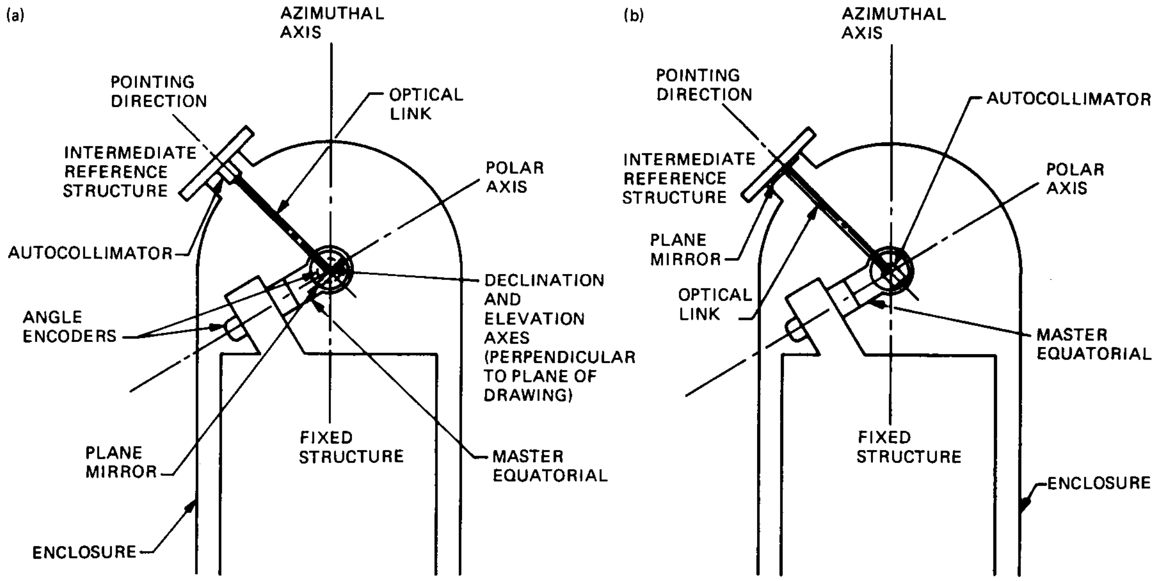

Fig. 1. Pointing-metrology system for the 70-meter antennas. In (a) the antenna follows the master equatorial; in (b) the master equatorial follows the antenna.

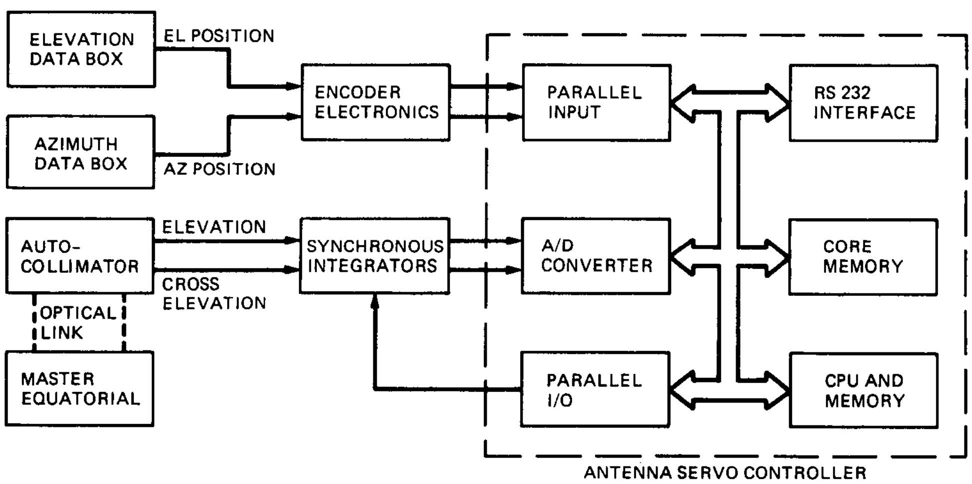

Fig. 2. Block diagram showing signal flow from the autocollimator to the antenna control system

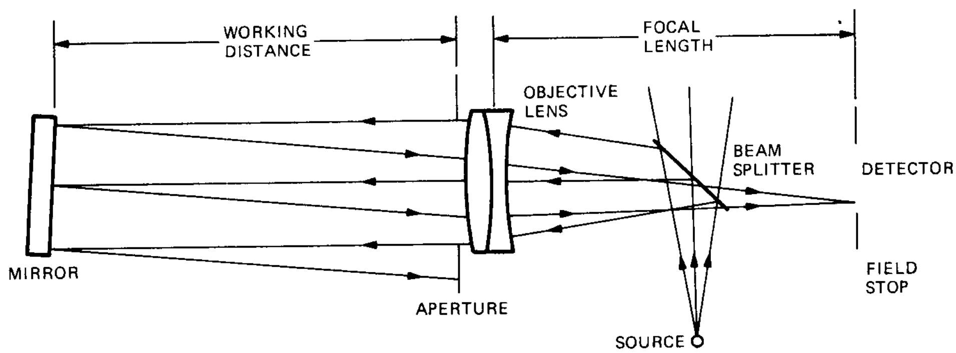

Fig. 3. General autocollimator configuration. The source and detector may be interchanged.

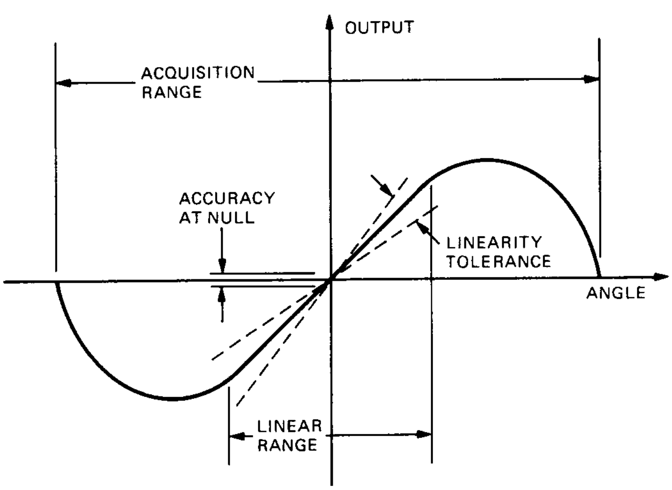

Fig. 4. Typical autocollimator transfer curve showing the relationships among several parameters

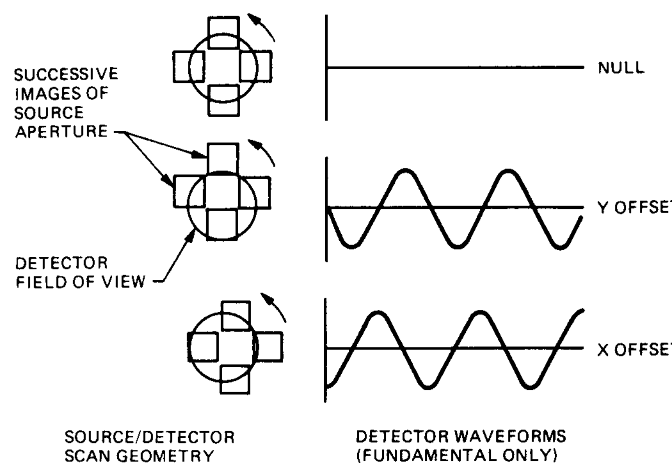

Fig. 5. Mechanical scanning used in the Kollmorgen model 874 autocollimator. The waveforms for representative offsets are shown.

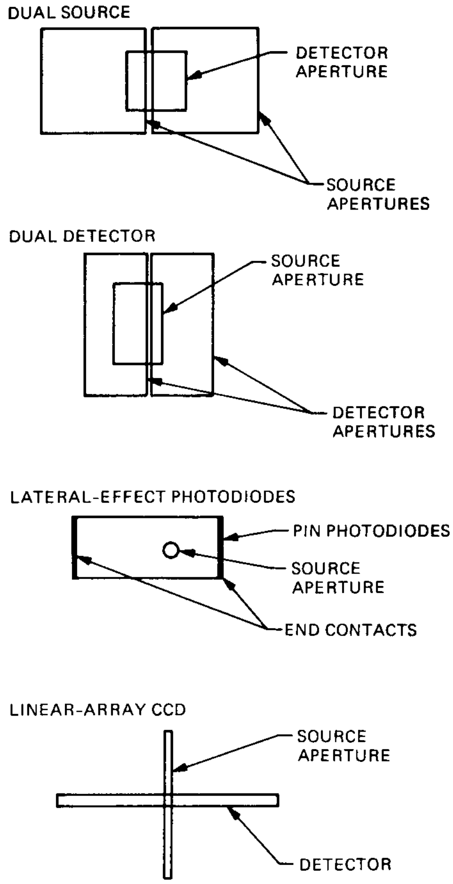

Fig. 6. Non-scanning detection schemes used in commercial autocollimator

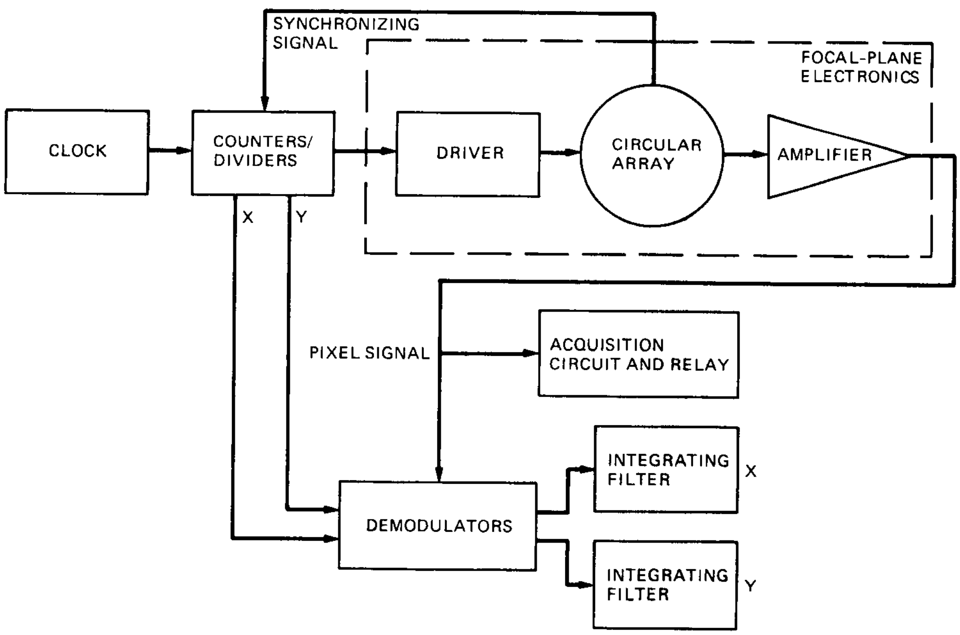

Fig. 7. Block diagram of the circular-array detector implementation in model 874-64