

# Circle scanning systems of the U.S. Naval Observatory

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**Summary.** The transit circle telescope is a well known astrometric instrument which produces accurate right ascensions and declinations of celestial objects. This paper is primarily concerned with systems developed at the U.S. Naval Observatory to read divided circles electronically and subsequently generate more precise declinations of the observed objects. The development of these sophisticated circle scanning systems has led to the discovery of short period instabilities of the circles.

**Key words:** scanning systems – circles – micrometer – CCD

## 1. Introduction

A transit circle uses a large graduated circle to determine the declination position angle of the telescope. The circles are usually either engraved metal circles or glass circles with the divisions deposited on their surface (Rafferty and Klock, 1982). Readings of the position angles were first done visually using microscopes mounted on the cage of the transit circle. The microscopes were mounted in pairs 180 degrees apart to eliminate the influence of the eccentricity error caused by the difference in the physical center of rotation of the circle and the center of the circle. Between 1941 and 1971 the U.S. Naval Observatory (USNO) utilized a photographic method of reading the four circle microscopes of the six-inch transit circle similar to that adopted at the Hamburg Observatory (Dolger, 1937). After the seven-inch transit circle was placed into operation in 1955, a similar scheme for reading its circle was implemented. During the final 16 years of operation with the photographic method, the films were measured with a photoelectric measuring engine developed by Watts (1950) and improved by A. N. Adams. Over 600,000 observations were made on the six and seven-inch transit circles using the photographic method. Even though it had a number of shortcomings, the technique represented the state-of-the art during its era. The major difficulty encountered was that the turn-around-time between taking a photograph and calculating an observed position for the object in question was too lengthy. In heavy observing periods this interval was frequently as high as several months. Other problems

were the loss of observations from faulty film development and the delayed discovery of a misadjusted camera.

In 1968 a photoelectric circle scanning micrometer was loaned to the USNO by Brorfelde Observatory. This micrometer had been developed under the guidance of S. Lausten (Einicke, 1971) and served as the forerunner of several photoelectric circle scanning systems subsequently developed by the USNO. The scanners used at Brorfelde used a photomultiplier tube, whereas the systems developed by Watts Prototype, Inc. for the USNO were solid state devices using a photodiode detector. The first two systems were developed for the six-inch transit circle and the automatic transit circle (ATC), the latter being modified in 1981 to become a conventional eight-inch transit circle. In the mid-seventies another system was constructed with the aid of an international NSF grant. This system was installed in Sao Paulo, Brazil in 1975 and served as the forerunner for a much more accurate system constructed by Watts Prototype, Inc., in 1983 and installed on the USNO seven-inch transit circle. A similar system was installed on the six-inch transit circle in 1984.

Due to some shortcomings of the photoelectric scanners, which will be presented in detail later in this paper, a prototype scanner using a charge coupled device (CCD) has been built and is currently undergoing testing.

## 2. Photoelectric micrometer development

With the rapid evolution of electronic technology in the late 1960's the USNO, in collaboration with Watt's Prototype, Inc., developed six miniature, highly precise measuring engines, to replace the old photographic cameras on the end of the microscope tubes. The overall arrangement is illustrated in Fig. 1. A geared synchronous motor turns a precision screw, which in turn moves a slide guided by a tangent arm attached to a cylindrical ground rod. On the slide is mounted the photodiode with a slit, shaped to about the same dimension as the division image it is to scan. The precision screw has a pitch of 100 threads per inch (tpi). Figure 2 shows the limit switches and the electronics board. The appearance of the circle divisions and fiducial wire as viewed through the eyepiece of a scanner micrometer are illustrated in Fig. 3. Initially, the six-inch and ATC scanning systems had glass plates in their focal planes, which had two fiducial lines scribed on the glass. They were separated so that they appeared one and one-half circle division intervals apart (0.075 degree). The plan was to set the telescope at

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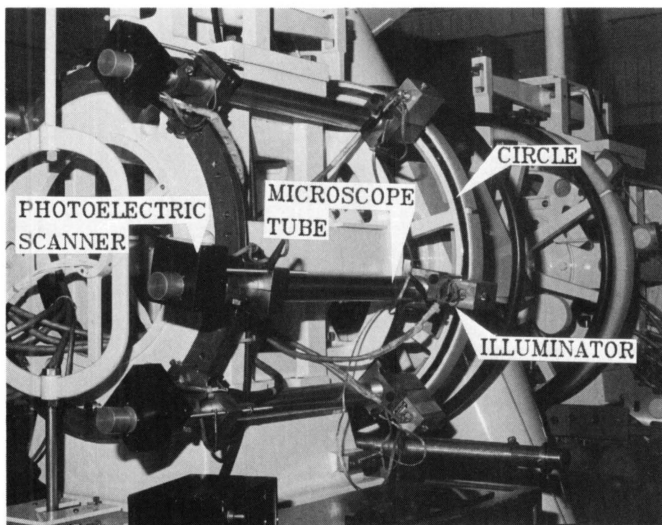
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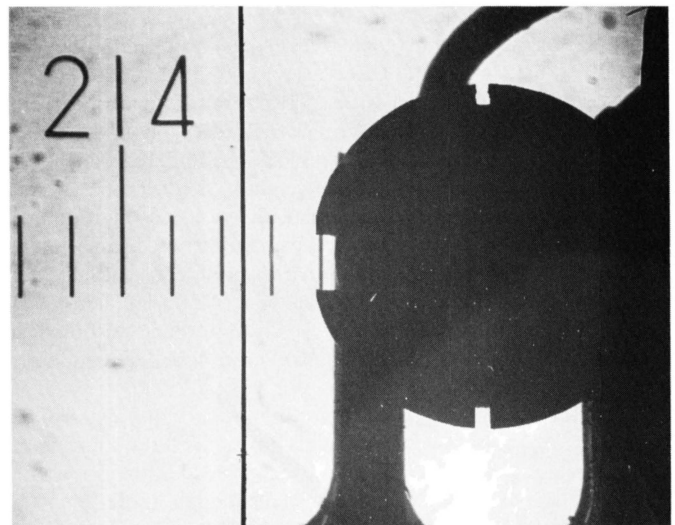
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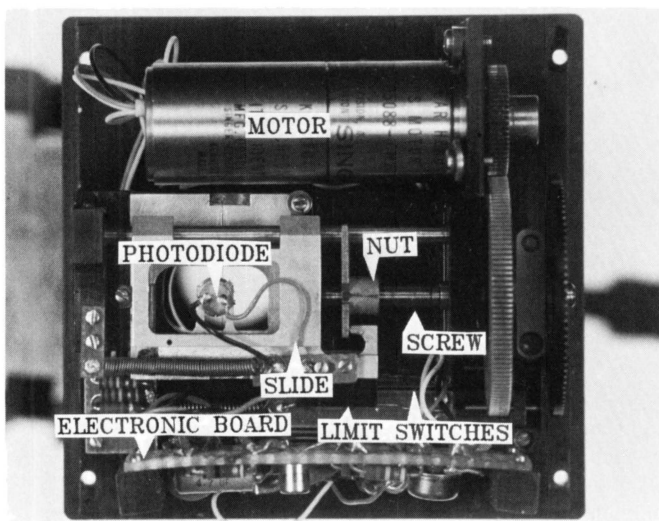
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**Fig. 1.** One of the cages of the six-inch transit circle showing the microscopes used to view the circle. The microscopes are about 54.6 cm long with the illuminators mounted closest to the circle and the photoelectric scanners mounted on the other end



**Fig. 3.** The appearance of the circle divisions and fiducial wire as viewed through the eyepiece of a scanner micrometer on the six-inch transit circle. The circular object to the right is the photodiode. The notches on the side of the photodiode are used for alignment of the unit



**Fig. 2.** The micrometer part of the photoelectric scanning system of the six-inch transit circle. A geared synchronous motor turns a precision screw, which in turn moves a slide guided by a tangent arm attached to a cylindrical ground rod. On the slide is mounted the photodiode and slit. A single fiducial wire is mounted in the focal plane of the scanner. Two magnetic limit switches control the range of motion. The dimensions of the scanner head are 8.25 cm by 8.25 cm by 5.0 cm

the best position to observe the star and if a division line came too close to one of the fiducial lines (so that it could not be properly resolved), then the other fiducial line would be used in the solution. Tests showed that the separation between the fiducial line and the division required to yield an acceptable solution was about 0.01 degree. In the realm of accuracy under consideration, the microscope tubes on which the scanners are mounted are in almost continual motion. The double fiducial lines were supposed to handle the drift problem; however, what was actually found was that frequently micrometers on opposite ends of a diameter were not 180 degrees apart but rather were 179.95 or 180.05 degrees. The

180 degree separation is an important requirement in order to properly eliminate the eccentricity error and also for proper application of the diameter correction. This situation was further accentuated in the circle used on the eight-inch transit circle since it had both a very large eccentricity error and large diameter corrections. This problem was successfully by-passed by setting the telescope for the best possible scanner results and then measuring the star slightly off the optical axis in declination. Since the double fiducial lines were not necessary, the glass plates were replaced with a single fiducial wire mounted in the scanner body.

On the USNO circles there are 7200 divisions or 3600 diameters. Each division interval is approximately 0.05 degrees or  $180''$ . Each division interval was divided into 5000 parts and the measurements fed to an IBM 1800 data acquisition and control system (later replaced with an HP 1000 computer). A real time algorithm detected the division and fiducial lines in the data and then a least squares solution was made to determine their positions. This software was developed by F.S. Gauss. The time for a single scan by the first systems was about six seconds, including the processing of the data points. This was vastly less than that required for a photograph to be taken, developed, and later measured on the film measuring machine. To check the performance of the scanners, it was decided to scan the circle twice so that a comparison of the results could be made. The double scan of the circles took about 12 s and was taken at the end of an observation.

### 3. Illuminators

The illumination of the circle was one of the critical areas of concern with the photographic method and this turned out to be of equal concern for the new systems under development. Many of the newer transit circles developed in other countries have circles made of glass that can be illuminated from behind. The instruments at the USNO were forced to use the steel wheels made originally for inlaid engraved metal circles. When the change was made to glass circles, a glass annulus was mounted to the steel

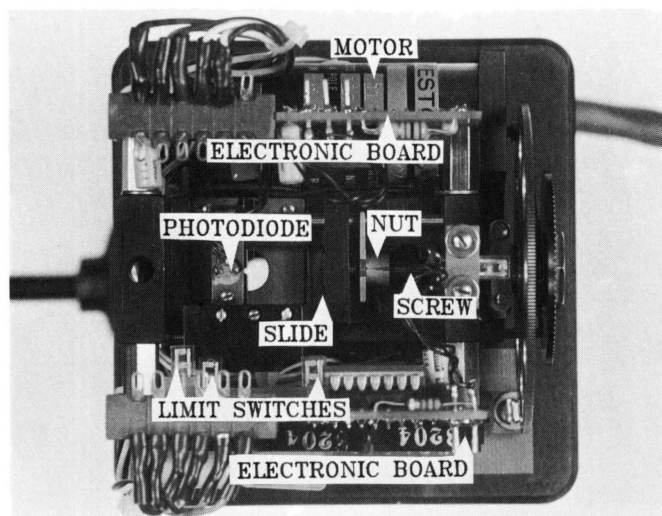
wheels and they were illuminated by reflected light (Rafferty and Klock, 1982). When the scanners were being developed in 1972, the USNO's transit circles still had engraved, gold metal circles with the division lines darkened with a special ink. Obviously it was desirable to have a high contrast between the divisions and the gold metallic background. One of the problems encountered was that of the uneven quality of the background. This problem was eventually solved several years later with the use of high quality glass circles. The contractor spent considerable time in an attempt to use a direct current (d.c.) illumination source. Eventually this effort was abandoned and the idea of a xenon-arc lamp was conceived. This proved to be a successful approach (although it created electronic noise problems), and was subsequently implemented.

The illuminators produced their "miniature lightning-stroke" by pulsing the xenon-arc lamp synchronously with the rotation of the micrometer screw. Each flash pulse produced a corresponding electronic output pulse from the micrometer photodiode which was in turn amplified before being sent to the data acquisition and control system. The excitation frequency was synchronized to the 400 Hz motor frequency. It should be noted that the xenon bulb had to be positioned radially with respect to the engraved, metal circle in order to maximize the background level of the light. The useful lifetime of the bulbs under normal observing conditions was about six months.

At the outset of the design of the Sao Paulo scanning system, every effort was made by the contractor to eliminate the xenon-arc lamp as the source of illumination. The Sao Paulo meridian circle had a high quality transparent glass circle, which was back illuminated. It had well-defined lines and consequently outstanding contrast. With the utilization of the glass circle, a small incandescent lamp was discovered which provided very good illumination. This concept was used with the seven-inch transit circle scanning system in 1983 as well as the new six-inch transit circle system in 1984. At that time, both telescopes were using circles with glass annuli containing the divisions mounted to them. Figure 4 shows the working components of the scanning micrometer for the seven-inch transit circle. The use of the incandescent, d.c.-powered bulb considerably reduced the electronic noise and significantly improved the repeatability. At their best the original systems would rarely repeat to better than 0.075 seconds of arc, whereas the Sao Paulo system and the new six and seven-inch systems are a factor of two better (see Table 1). It should be stressed that the change in the illumination was not the sole reason for the improvement in the repeatability. The other reason will be discussed in the next section.

#### 4. The system electronics

The first scanning systems for the six-inch transit circle and the ATC had identical electronic circuits. As previously mentioned, each pulse of the xenon-arc lamp resulted in a corresponding pulse from the photodiode. The pulse was then a.c. coupled through an operational amplifier located in the micrometer and then sent to the electronics rack in the control room. Here the pulse was shaped into a ramp function and then applied to a Schmitt-trigger circuit. The trigger output, depending on the threshold, turned a data counter on or off at a 1 MHz rate. The resultant binary number stored in the counter was sent to an IBM 1800. A pulse then reset the counter and started the process all over again. Thus the final result was a series of binary numbers stored in the computer and



**Fig. 4.** The micrometer part of the photoelectric scanning system of the seven-inch transit circle. The arrangement is basically the same as that of the scanner for the six-inch transit circle shown in Fig. 1. Two of the three limit switches are used to control the range of a scan. The third limit switch is used to move the photodiode to one side so that the fiducial wires and circle can be viewed for setting up the unit. The dimensions of the scanner head are 10.0 cm by 10.0 cm by 10.0 cm

**Table 1.** The performance of the various scanner systems used at the U.S. Naval Observatory. The scanner precision is how well a single scanner can repeat its measurement. The system accuracy is how well the system of six scanners can repeat a determination of the circle's diameter corrections. Since the USNO currently has only one CCD scanner, only an estimate of the accuracy based on its precision can be made

System	Scanner precision (arcsec)	System accuracy (arcsec)
Eight-inch	0.054	0.090
Six-inch (old)	0.075	0.072
Seven-inch	0.024	0.044
Six-inch (new)	0.025	0.043
CCD	0.025	(0.043)

serving as a numerical representation of the intensity profile of the division line, fiducial line, and circle background.

On the six-inch transit circle system the division and fiducial lines generally had about 20 to 25 data points. The nominal magnification of the microscope optical system was 3.4. Each division, when magnified, was about 70 microns wide in the focal plane of the photodiode slit. The width of the slit was approximately the same width as the magnified image of the division.

An increase in the number of data points for a line should theoretically improve the solution for the center of the line. An increase in magnification gave a corresponding increase in the number of data points for a line, however, to obtain this increase in magnification required an increase in the overhang of the micrometer from the microscope bearers. This degraded the mechanical stability of the system. Increasing the amplifier gain

similarly increases the electronic noise. Thus, with these factors in mind, an entirely different approach was adopted by Watts Prototype Inc. for the Sao Paulo electronics, and subsequently, the new six and seven-inch transit circle electronics.

For all three of the newer systems mentioned in the previous paragraph, an electronics system was developed which essentially integrated the area in the line profile with an analog filter designed by Dr. C. Hollins of Watts Prototype, Inc. This proprietary filter was tuned to the width of the slit and the fiducial and division line profiles. Unfortunately, the line profile of a division line never quite matches the profile of a fiducial line image. This was largely due to the diffraction limited performance of the optical system of the microscope tube. Since the fiducial line was immediately in front of the photodiode-slit combination, it did not undergo optical distortion.

The analog filter system, besides providing much better repeatability, also provides the spacings between the fiducial wires and the division lines, which reduced the work load on the computer. Instead of waiting until the end of an observation to scan the circle, these new systems can scan during the observations, so more scans can be taken. The newer systems could also scan in both directions, cutting the time for a double scan from 12 to six seconds.

## 5. The mechanical assembly

The weakest link in all of these systems constructed to date is the mechanical screw-slide combination. The screws selected to transport the slide and photodiode across the image plane were the best commercial precision screws available at the time. However, they were made from a soft stainless steel which had a much higher wear factor than a high carbon steel screw. Efforts were made to find a source for a precision hardened stainless steel screw which would exhibit little wear over an entire observing program. This research was successful and the new six and seven-inch scanning systems now incorporate precision hardened stainless steel screws. This was particularly important for the seven-inch transit circle since the screws are operated at a very high speed.

Each of the new screws must be examined for screw errors in order to select the screws with the smallest errors for use in the systems. It is of particular importance to note that the screw errors for some of the screws were found to introduce significant changes in the measured separation between the divisions.

Initially the seven-inch system was set up to scan over three divisions and two fiducial wires. This is illustrated in Fig. 5. This was due to the nature of the new main telescope micrometer which featured an image dissector with fixed declination wires. It was presumed that the rather narrow field of view of the dissector micrometer would inhibit the flexibility in setting the telescope so that the division lines would likely fall on or near the fiducial wires. Thus when a scanning system was needed for the refurbished seven-inch transit circle, the question of double fiducial wires arose once again. The main micrometer of the seven-inch transit circle had no declination adjustment and initially it was thought that the telescope would have to be set to place the star very close to the center of the optical declination axis.

The seven-inch scanning system was delivered with two fiducial wires. Once again the drifting of the microscopes was a concern. An even greater problem arose with the discovery that the diameter corrections of the new glass circle were extremely large. In an attempt to alleviate the problem, tests were conducted to determine the distance from the optical axis that the image dissector

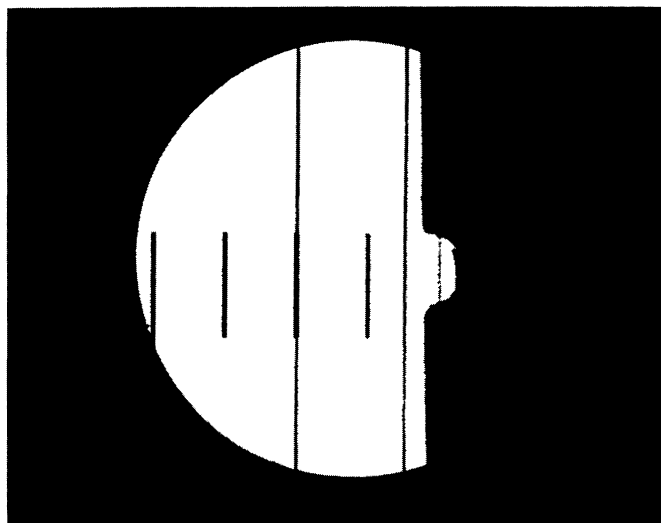


Fig. 5. The appearance of the circle divisions and the two fiducial wires as viewed through the eyepiece of a scanner micrometer on the seven-inch transit circle. The object to the right is the photodiode. The notch on the side of the photodiode is used for alignment of the unit

micrometer could reliably operate. It was found that its geometrically linear field of view was large enough to allow the telescope to be set for the optimum scanner position and permit the use of only one fiducial wire.

## 6. A charge-coupled device scanner

The USNO is currently testing a prototype scanner that incorporates a Charge Coupled Device (CCD) to eliminate the screw, the fiducial wires, and all of the moving parts of the existing systems. It should be noted that the new Tokyo meridian circle has already adopted a similar approach (Miyamoto, 1982). However, the Tokyo system employs a linear diode array. This technique was initially considered by the USNO, but concern over the possible tilt of the micrometer arising from the mechanical drift of the microscope tubes led to a decision to abandon this method. Instead a CCD area array is used. The array has 491 rows of 384 pixels each. The spacings are 23 microns horizontally by 13.4 microns vertically. Due to the spacing of the pixels, a high magnification of the image of the circle is necessary. On the Tokyo system, since the use of the linear array scanners was in the original plans for the instrument, the cages were designed to be very long in order to support the long microscope tubes that allow the image of the circle to be magnified by about 13 times. The USNO's CCD scanner is being developed on the Six-inch Transit Circle in Washington, DC and the length of the microscope tubes used are limited to the dimensions of the existing cages. It is desirable to place the lens and scanner close to the two microscope supports so that the system will be stable. The optics for the CCD scanner are mounted on the end of the microscope tube which is about two inches in front of the forward microscope support where the optics for the present photoelectric scanners were placed. A magnification of 6.5x is achieved with this arrangement compared with 3.4x with the old. Video output of the CCD allows for alignment of the scanner. Figure 6 shows the image of the circle and the alignment wires in the plane of the CCD array. To eliminate the unpredictable effects of scanning the ends of the division lines, only the center 128 by 255

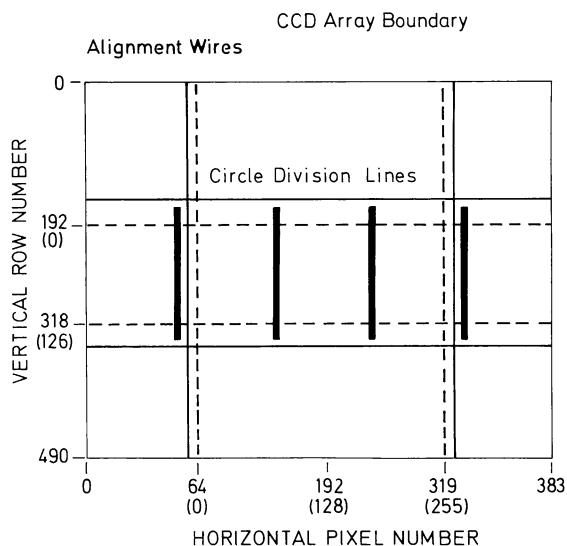


Fig. 6. A diagram of the image of the circle and alignment wires in the plane of the CCD array. The dashed lines outline the central part of the array that is used to determine the positions of the circle division lines

pixels of the array are used. The CCD uses interlaced scanning which allows two separate groups of rows to be scanned. The illumination for the CCD scanner is the same as that used for the newer mechanical scanners, except an auxiliary lamp was added to provide a uniform illumination of the CCD array without the presence of the division lines. This uniform illumination can be used to check for defective pixels or dirt on the CCD array window.

The scanning time of the CCD scanner was matched to that of the mechanical scanners (about six seconds) so that comparisons could be made under observing conditions. During a single scan of the mechanical scanners, the CCD can sample the center 128 by 255 pixel area twenty times. The position of the divisions is referenced to a column of pixels at the center of the field, thus eliminating the need for a fiducial wire. The twenty samples can be compared to test for problems with the unit. By sampling different parts of the divisions, the effects of tilting of the scanner with respect to the circle can be eliminated in the solution. Changes in the focus do not degrade the precision of the CCD scanner as it does for the mechanical scanners since no slit, that must closely match the image of the division, is used in the measurement process. The precision of the CCD scanners was found to be about the same as that of the newest mechanical scanners (see Table 1). Improvement of the precision might be made by increasing the magnification of the microscopes, but would likely cause a stability problem. Even with equal precision, the CCD scanner is superior to the mechanical scanners in that the problems related to the micrometer screw, the wear of the moving parts and the fiducial wire are eliminated. Thus the telescope could be set to the stars and the observations could be well centered, which is an important

feature for instruments that will use electronic detector micrometers.

## 7. The circles

With the increased precision of the new scanning systems, improvements in the accuracy of the determination of the pointing of the telescopes were both expected and noted. However, the improvement in the accuracy of the pointing did not match the improvement in the precision of the scanning (Table 1). This difference is likely caused by changes in the glass circle. Due to the problems with earlier glass circles used at the USNO, a scheme of checking for long term changes in the circles had been developed. Determinations of subsets of diameter corrections were taken numerous times during a year. By taking numerous sets of data on the circles on the same day with the newer scanning systems, short term changes in the circles, likely related to temperature, were noted. In the case of the eight-inch transit circle in Flagstaff, Az, large changes in the shape of the circle were seen. These changes were caused by a design flaw in the steel wheel which caused changes in its shape under the slightest change in stress and temperature. These changes were modelled so useable declinations could be determined with the instrument. The circles on the six-inch and seven-inch transit circles also show small, daily changes, ranging from about 0'02 to 0'06. (These changes are currently under investigation and will be reported in a future article.) At the level of precision the scanners are now operating, it is not surprising that these changes can be seen. The metal and glass, as well as the mounting stress on the steel wheel are surely affected by temperature, and these changes cause variations in the positions of the divisions on the circle.

## 8. Conclusions

The quality of real time scanning of the circles of the USNO's transit circles has increased significantly since 1971. The problems encountered with the mechanical scanners are greatly diminished with the CCD scanner. The limitations of the CCD scanner appear to be dependent on the magnification and stability of the microscopes, although the ultimate limitation may be the stability of the circles themselves.

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