Cometary Astrometry

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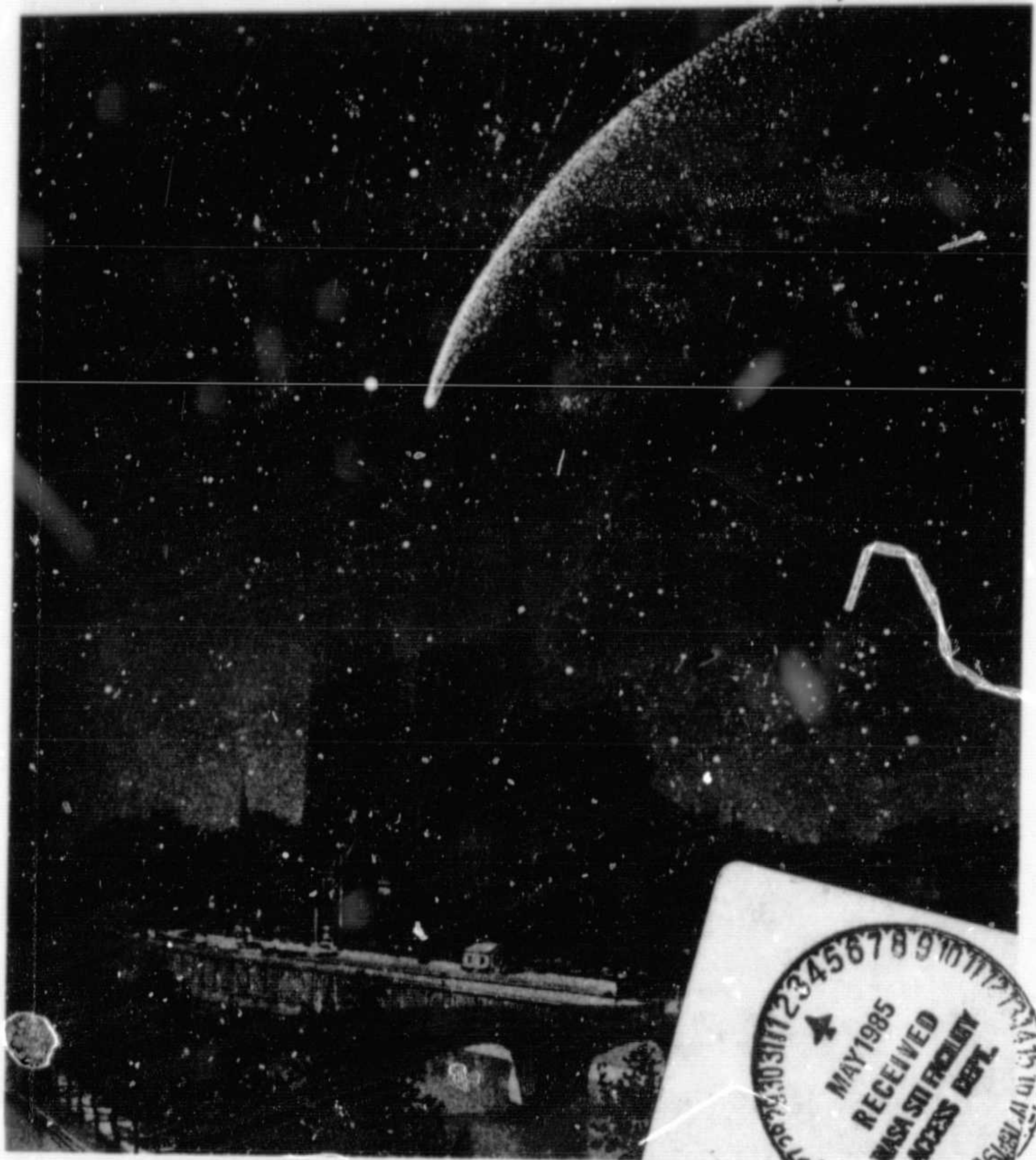

Cometary Astrometry

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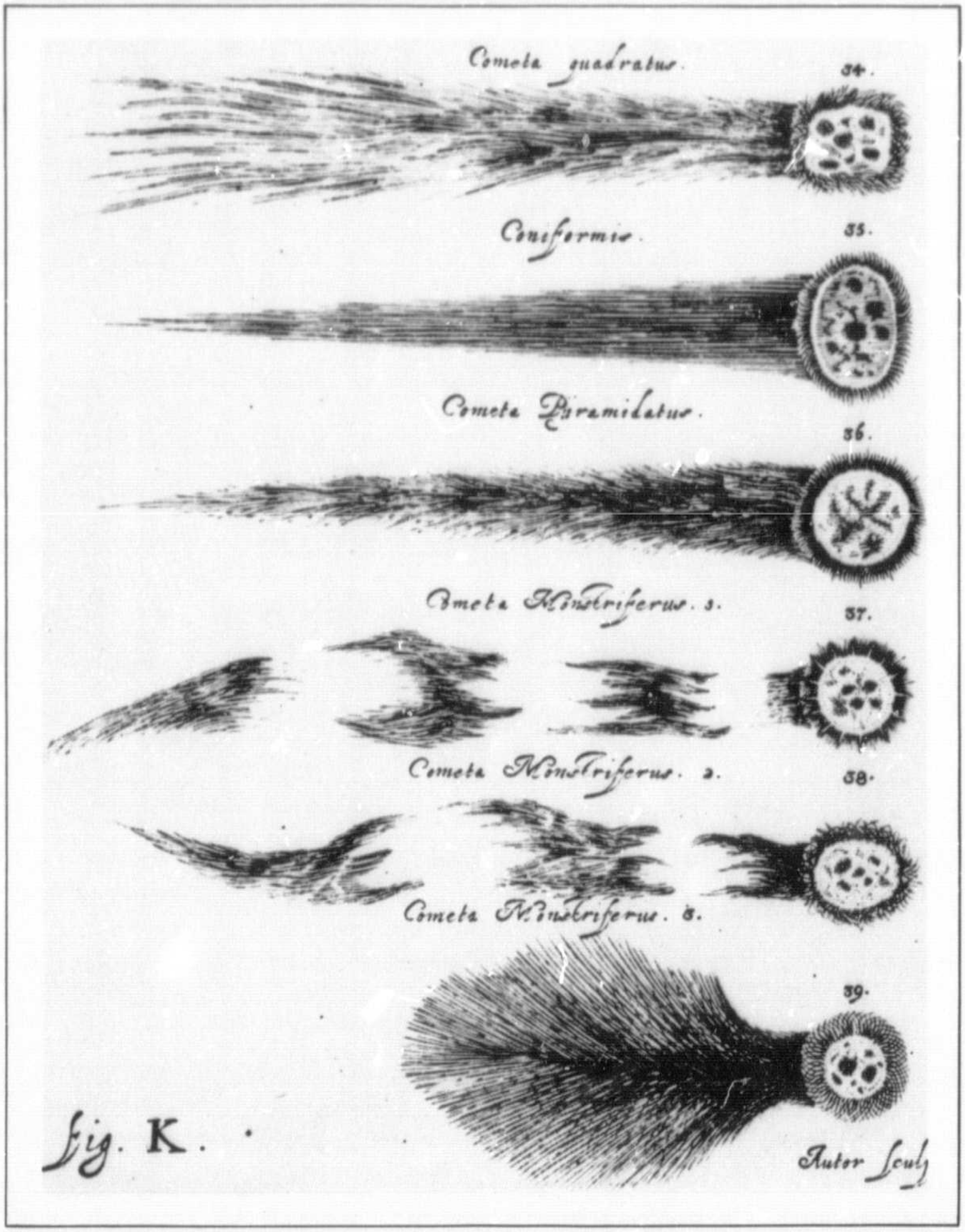

Illustration of cometary forms from the 1668 **Cometographia** by Johannes Hevelius.

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WELCOMING ADDRESS

On behalf of the European Southern Observatory, I am happy to welcome all of you to Garching. The meeting which we are about to start is unique in several respects: it is the first major one organized by one of the International Halley Watch (IHW) nets, it aims at a specific project, i.e., to put together clear recommendations how to do first-class cometary astrometry and, not the least, it must be one of the few meetings ever held where professionals and amateurs come together to exchange experience.

It is good to see that more than 20 nations are represented in this auditorium. When the IHW was first created, it was felt in some quarters that it had a somewhat local character. However in 1982, after the International Astronomical Union recognized the IHW as the world coordinating agency for Halley programmes, a rapid expansion took place and it became a truly international organization. This is amply demonstrated by the fact that scientists from all continents are here today.

I am sure that we shall have a most useful and interesting workshop. Please remember that the final outcome depends on the active participation of all of us!

I wish you all a pleasant and profitable time at ESO.

Richard M. West

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N85-25016

THE ASTROMETRY NETWORK OF THE IHW AND THE P/CROMMELIN TRIAL RUN RESULTS

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THE ASTROMETRY NETWORK OF THE INTERNATIONAL HALLEY WATCH

The general goals of the International Halley Watch (IHW) are to encourage observations of comets Halley and Giacobini-Zinner, to help coordinate those observations and to archive the data in an organized fashion. The two lead centers for the IHW are located at the Jet Propulsion Laboratory in Pasadena, California, U.S.A. (under the direction of Mr. Ray Newburn) and at the Remeis Sternwarte in Bamberg, FRG (under the direction of Dr. Jurgen Rahe). The seven established observing networks of the IHW include the following:

- Astrometry
- Infrared Spectroscopy and Radiometry
- Large Scale Phenomena
- Near Nucleus Studies
- Photometry and Polarimetry
- Radio Studies
- Spectroscopy and Spectrophotometry

At this writing, there are approximately 875 astronomers from 47 different countries cooperating with the IHW. There are at least 3000 more amateur astronomers who have expressed an interest in making observations as well.

Our Astrometry Network is fortunate to have the participation of more than 200 astronomers from 42 different countries. The goals of our Astrometry Net are to establish a world-wide network of astrometric observers who are willing to provide timely and accurate astrometric observations of both comets Halley and Giacobini-Zinner. These important observations will then be used to generate up-to-date orbits and ephemerides for ground based observers, earth orbital spacecraft and interplanetary spacecraft. This latter class includes five spacecraft that are being plannned to fly by comet Halley in March 1986 and one spacecraft that has been targeted to fly by comet Giacobini-Zinner in September 1985. None of the flyby spacecraft have the capability to perform on-board navigation. To a large extent, the accuracy with which these spacecraft encounter the comets will be determined by the accuracy of the predicted cometary ephemerides and these ephemerides will in turn depend upon accurate astrometric positions of the comets.

WORKSHOP OBJECTIVES

The objectives of this workshop are to discuss current techniques and make recommendations for making cometary astrometric observations, reducing these observations, employing accurate reference star catalogs and ultimately determining precise orbits and ephemerides.

COMET CROMMELIN TRIAL RUN RESULTS

In an effort to test the techniques and communication lines of the entire IHW organization, comet Crommelin was selected as a comet that would act as a trial run or rehearsal for the future observations of comets Halley and Giacobini-Zinner. Astrometry network members were asked to provide a few observations of comet Crommelin during a period within a few months on either side of the comet's perihelion passage (1984 Feb. 20). Special comet Crommelin star catalogs were distributed to Net members and each observer was asked to observe, reduce and transmit their data as quickly as possible. Some 372 astrometric observations from 42 different observatories were received at the orbit determination center making this apparition of a short periodic comet the best observed in history. Data were received by phone, mail, telex, and electronic mailbox. Orbit information and up-to-date ephemerides were computed and distributed by the same communication channels. Each of the other Observing Network headquarters were provided with an ephemeris generation program and up-to-date orbital elements for initializing these programs were always available in the IHW electronic mailbox.

All the astrometric data received was tested in the orbit determination system and observations that were more than three times the root mean square residual were excluded from future orbit determination solutions. As might be expected, the most accurate data were generally received from the most experienced observers. For the final orbit solution, 61% of the received astrometric data was used. Each observatory that participated in the comet Crommelin trial run received a listing of the orbit residual for their particular observatory. It is our hope that these residual listings will enable observers to determine where they might make improvements for their future astrometric observations. All the astrometric data received at the orbit determination center has been placed in a master data file, and archived on magnetic tape in a standard IHW data format.

The comet Crommelin trial run was successful in pointing out some areas that need to be improved to make the data more accurate and the communication channels more efficient. Many observers did not employ the special Crommelin reference star catalog and while this catalog was merely a selection of SAO stars along the comet's path, it was hoped that observers would use this catalog to familiarize themselves with the data format that has been used in constructing the special Halley and Giacobini-Zinner reference star catalogs. It should be emphasized that a consistent, unbiased data set for both comets will depend upon observers using only the special reference star catalogs that have been made available. In the future, observers should make an effort to send their data electronically (Telex, electronic mailbox) so that this data can be automatically read and catalogued without manual data re-entry at the orbit determination center.

DISCUSSION FOLLOWING PRESENTATION

L.G. Bowell: What is the overall RMS residual for the Crommelin observations, and were these observations of sufficient quality to satisfy the scientific requirements of the mission planners.

D.K. Yeomans: The overall RMS observation residual for the 226 astrometric observations (1983-84) used in the orbit fit was 1.67 arc seconds. While this RMS value is on the order of what we hope to achieve for comets Halley and Giacobini-Zinner, I should point out that of the 372 total observations received, only 61% of these were used in the orbit fits. Clearly many observers need to improve their accuracy before their observations can be used in future orbit determination solutions.

N85-25017

D2

CURRENT IDEAS ON THE NATURE OF COMETS

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THE NUCLEUS OF A COMET

At distances from the sun of more than about 10 AU a comet consists in effect of a solid core that merely shows a reflected solar spectrum. In telescopes it has an almost starlike appearance, its brightness being given essentially by the product of its reflectivity or albedo, A, and the cross-section area of the nucleus ($S = \pi R^2$). The product AS can be deduced from nuclear brightness observations at large heliocentric distances when the light contribution of the coma is practically negligible relative to the brightness of the nucleus.

Photometric and radar observations yield values for cometary radii of the order of 0.5 to several km; the radii of short-period comets are on average a few km smaller than those of nearly parabolic "young" comets, implying a reduction in radius of several m per revolution.

The details of the structure of the cometary nucleus and its chemical composition remain as yet model-dependent. According to the generally accepted "icy-conglomerate model" proposed by Whipple (1950, 1951), the nucleus is a porous body of frozen components, with micron-sized particles of meteoric matter (metals, silicates, etc.) embedded in it. As the distance from the sun decreases, solar radiation heats the solid nucleus of frozen gases, releasing dust particles and gas molecules (parent compounds) which are photodissociated into radicals and atoms. These fragments form an almost spherical atmosphere or coma around the nucleus. The micron-sized dust particles scatter the solar radiation and produce a continuous spectrum superimposed upon the molecular band and atomic line emissions.

THE ATMOSPHERE OF A COMET

The radius of the coma as seen from the ground extends to 10^5 to 10^6 km. One finds compounds of C, N, O and H, and near the sun also terrestrial atoms such as Na, Si, Ca, etc. In the far UV, the $L\alpha$ - line of H dominates the spectrum, in the IR we have essentially scattering and radiation from solid particles.

Of all coma molecules observed from the ground, CN shows the greatest extension (up to 10^6 km). The (0,0) transition at 3883 Å is by far the strongest and determines the shape and diameter of the coma in the photographic spectral region. The Swan system of C_2 does the same in the visible. C_2 extends to several times 10^5 km. Then come OH and NH (10^5 km), then C_3, CH, NH_2 (5×10^4 km). The emissions decrease gradually with increasing nucleocentric distance, and their extensions are not sharply defined.

All molecular compounds observed optically in the coma are radicals, which implies that the densities must be very low; most emissions are produced by a resonance-fluorescence mechanism. The intensity irregularities observed, e.g., in rotational lines of the CN (0,0) band, are clearly correlated with Fraunhofer absorption lines in the solar radiation.

The identity of the parent molecules in comets is still a problem. A correlation with interstellar molecules is an attractive possibility, since many of the radicals identified in cometary spectra look like dissociation products of observed interstellar molecules, but until now, only a few parent molecules (H_2O, HCN, CH_3CN) have been recorded in cometary spectra.

THE TAILS OF A COMET

The plasma tail of a comet as seen from the ground consists of molecular ions, predominantly CO^+ with contributions from H_2O^+, N_2^+, CO_2^+, CH^+ and OH^+. The ions usually appear when the comet has a heliocentric distance of less than 2 AU; exceptions, however, are known. Humason's Comet (1962 VIII), for instance, showed a strong CO^+ emission at over 5 AU from the sun.

Dust tails show a reflected solar spectrum. Photometric and polarimetric studies reveal that they consist of dust particles with diameters typically of the order of 1 μm.

ULTRAVIOLET OBSERVATIONS

Ultraviolet observations are for cometary studies especially important (e.g., Rahe, 1983) since the major atomic species H, O, and C, have their strongest transitions between 1200 and 1700 Å.

Already the first UV observations of a comet proved the existence of an enormous H-cloud surrounding the cometary nucleus. The subsequent study of the H and OH emissions in a number of comets, strongly supported Whipple's (1950) original model of the nucleus, and the typically found H_2O production rates of 10^{29}-10^{30} molecules/sec are of the same order of magnitude as those predicted by him already in 1950 from the analysis of non-gravitational forces.

For Comet Kohoutek, e.g., one finds at 1 AU, about 3×10^{29} molecules/sec, or a total mass loss of H_2O of 10^{15} g, which is about 1% of the total mass. The short-period Comet Encke has been in the inner solar system for a long time; it seems to have lost most of its volatile material and has a much smaller evaporation surface. Encke's H_2O-production rate is more than one order of magnitude smaller than that for bright "new" comets.

Another very interesting result of UV observations is the following: especially with the IUE-satellite, a number of different comets have been observed. Several comets were observed at identical heliocentric distances, others at various heliocentric distances; they looked very different. They showed a different gas-to-dust ratio and some of them were quite "old", others rather "new". Only the dust, and the CO^+ abundances seem to vary from one comet to the other. If one compares, e.g., the spectrum of a "new" comet, such as Comet 1978 XV Seargent (Jackson et al., 1979) with the spectrum of an "old" comet, such as Comet Encke (Weaver et al, 1981), one finds an amazing similarity. In fact, the UV spectra of all comets observed so far, are practically identical. The strongest emissions, i.e., those of the most abundant species in the coma, are the same in all UV spectra obtained so far. The presence of the weaker emissions, i.e., those of the minor species, apparently depends only upon the comet's heliocentric velocity (so that the excitation factor remains large enough) and the instrument sensitivity (Festou et al, 1982). It should, however, be noted that as yet, e.g., no extreme CO^+-rich comet such as Comets 1908 III Morehouse or 1962 VIII Humason, have been observed in the UV.

Summarizing these results with regard to the character of the cometary nucleus, we can perhaps conclude that several observations appear to point to an undifferentiated structure: the continuum-to-emission intensity ratio appears to have a similar distribution for "new" and for short-period ("old") comets (Donn, 1981). These extreme age groups show no difference in the dust/gas ratio or the character of the solid particles, and there seems to be no qualitative change in cometary spectra as they evolve.

The emission spectra of new and periodic comets were found to be remarkably similar, in the visible as well as in the ultraviolet spectral region. Narrowband filter photometry (Vanysek, 1976; A'Hearn, 1982) showed that the CN/C_2 production rate ratio was quite constant from comet to comet, except for a well defined variation with heliocentric distance. The relative production rates, specifically of CN, C_2, C_3 and OH, appear to be unrelated to either the emission-to-continuum, i.e., (gas-to-dust) ratio, or the dynamical age of the comet.

Of the seventeen fragmenting comets studied by Sekanina (1979) which have well-determined orbits and were not sun-grazers, four were periodic, five old, and 8 new or nearly new. There does not seem to be any significant difference among the three age categories. If splitting is intrinsic to a comet, the nuclei of "new" and very old comets behave similarly.

From all this, we can perhaps conclude that the comets observed so far, have a very similar, homogenous chemical composition, and perhaps also a common origin.

INFRARED OBSERVATIONS

Recently, important new measurements of comets have been obtained in the infrared spectral region. To mention only a few, M.S. Hanner et al, (1984), obtained spectra of the central core and surrounding coma of Comet IRAS-Araki-Alcock (1983d) at 8-13 μm. Their spatially resolved measurements at 10 μm with a 4" beam showed that the central core of the comet was more than 100 times brighter than the inner coma which was only 8" away. These observations are consistent with the direct detection of the nucleus having a radius of approximately 5 km. Spectra of the core are featureless, while spectra of the coma show weak silicate emission. The spectra show no evidence for icy grains. The dust production rate on 11 May 1983 was determined to amount to about 2 x 10^5 gm/sec.

In his study of the discovery of a shell of particulate material around the star Vega by the IRAS satellite, P.R. Weissman (1984) discusses the question of whether this material is of cometary or asteroidal origin. He gives arguments that at the mean distance and temperature of the shell, the expected condensation products from a protostellar nebula would be dominated by frozen volatiles, in particular water ice, and points out that the Vega shell is likely a ring of cometary bodies with an estimated minimum mass of 15 earth masses, analogous to one that has been hypothesized for the solar system. A possible hot inner shell around Vega could be an asteroid-like belt of material a few AU from the star.

We can be assured that with the approach of comets, especially Halley's Comet, and the availability of new detector systems and models, exciting new discoveries will be made.

REFERENCES:

A'Hearn, M.F.: 1982, Comets, ed. L.L. Wilkening, Univ. Arizona Press, Tucson, USA, pp. 433-460.

Festou, M.C., Feldman, P.D., Weaver, H.A. and Keller, H.U.: 1982, 3rd European IUE Conference, Madrid, in press.

Jackson, W.M, Rahe, J., Donn, B., Smith, A.M., Keller, H.U., Benvenuti, P., Delsemme, A.H. and Owen, T.: 1979, Astron. Astrophys. 73, pp. L7-L9.

Hanner, M.S., Aitken, D.K, Knacke, R., McCorkle, S., Roche, P.F., Tokunaga, A.T.: 1984, Icarus.

Rahe, J.: 1983, Highlights of Astronomy, 6, 333, R.M. West, ed.

Sekanina, Z.: 1979, Icarus 38, pp. 300-316.

Vanysek, V.: 1976, The Study of Comets, NASA SP-393, pp. 1-27.

Weaver, H.A., Feldman, P.D., Festou, M.C., A'Hearn, M.F. and Keller, H.U.: 1981, Icarus 47, pp. 449-463.

Weissman, P.R.: 1984, Science, 224: 987-989.

Whipple, F.L.: 1950, Astrophys. J. 111, pp. 375-394.

Whipple, F.L.: 1951, Astrophys. J. 113, pp. 464-474.

DISCUSSION FOLLOWING PRESENTATION

R.S. Harrington: To illustrate how fast our ability to study comets is progressing, Jack Brandt has suggested that we may never again have the excitement of a Halley recovery, since we may never lose it.

B.G. Marsden: I disagree, because although it has been possible to observe comets that are as bright as 20th magnitude for some decades, fewer observations of 20th-magnitude comets are in fact being made than in the past. Furthermore, I still maintain that P/Halley was recovered when it was only because it had become active. Comets at distances where they are basically inactive are very much harder to detect, and judging by recent failures to detect ordinary Jupiter-family short-period comets near aphelion, those distances are not necessarily tremendously large.

P.R. Weissman: George Aumann of the IRAS team has just reported that IRAS found Vega-like shells around approximately 30 stars in the solar neighborhood, many of them solar-type F and G stars. This is about 6-10% of all local stars. Thus, Oort clouds may be a fairly common phenomenon in the Galaxy.

D3

N85-25018

NEAR-NUCLEUS STUDIES OF COMET HALLEY

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ABSTRACT

Quantitative studies of the near-nucleus dust coma structure of Comet Halley are possible using modern digital image processing techniques on photographs taken in 1910. We review recent investigations carried out in conjunction with the Near-Nucleus Studies Net of the IHW to better understand the characteristics and behavior of Comet Halley. A new image processing algorithm developed to enhance coma feature boundaries permits their evolution over as many as three days to be followed. The features can be modelled to derive information on the nucleus spin vector, particle sizes, ejection velocities and distribution of emission areas on the nucleus. Useful contributions by observers in the Astrometry Net are also discussed.

INTRODUCTION

The objectives of near-nucleus studies are to understand the processes acting in the coma on the material driven from the nucleus by sublimating volatiles and to examine what these processes can tell us about the physical properties of the nucleus. The purpose of our present study has been two-fold: 1) to devise and improve methods of identifying, measuring and modelling coma features for application to the data anticipated from the Near-Nucleus Studies Net (NNSN), and 2) to characterize the spatial and temporal distribution of coma material in the coma of Comet Halley in 1910. From the latter, we can better design and prepare imaging experiments for the 1985-86 period when the coma can be best studied. We hypothesize that by studying the spatial and temporal distribution of the various components of the coma, insight of the initial conditions of ejection can be gained. Ejection characteristics depend upon nucleus spin axis orientation, distribution of discrete emission areas (gross surface morphology), emission velocities and local elevation of the sun. Data obtained by the NNSN should permit studies of all components of the coma with sufficient spatial and temporal sample resolution to address many other problems not discussed here. We presently focus on the dust particles and their dynamics.

Our method of study of the nucleus emission process exploits the presence of anisotropic ejection of dust from the nucleus. The observed coma features are space density variations along the line of sight, serving as tracers of nuclear activity. The largest body of data on coma structure of Comet Halley exists in the form of visual drawings from previous apparitions. Unfortunately, it is essentially impossible to evaluate the quality of such data. The telescopic drawings show the existence of numerous coma features that change on a nightly time scale and are sometimes quite complex (Rahe et al, 1969). The 1910 apparition saw the application of photography to Comet Halley for the first time and the opportunity to use data on coma structure unhindered by observer biases (Bobrovnikoff,1931; Perrine, 1934).

The use of photographs is not without problems, however. Because of the steep intensity gradient from the nucleus to the outer coma resulting from the predominantly radial outflow of material, the long dynamic range of intensities to be recorded is usually outside the capabilities of most photographic emulsions. The most severe problem is that coma features are of very low contrast and superimposed on the general coma background gradient. Other problems include defects and chemical alterations that have taken place over the 70 years these plates have been stored.

Coma features change rapidly enough that their identity from night to night is often uncertain. The only solution to this problem is to combine photographs taken at several longitudes. We surveyed the available photographs and borrowed the original plates or film copies from collections at the Mt. Wilson, Lick, Helwan, Vienna and Heidelberg Observatories. Over 80 plates were digitized that cover a span of 33 days continuously except for five days around inferior conjunction.

IMAGE PROCESSING

Modern digital image processing techniques, which were not available to the astronomers who took the original plates, offer powerful tools for extracting positional data on coma features. Some common image enhancement techniques were tried on the digitized images, but most had drawbacks that could lead to possible misinterpretation. It is not enough to simply "stretch" the contrast to see the low contrast feature boundaries, because the coma brightness gradient would merely produce a single isophote at some intensity level. Spatial filtering algorithms often introduce artifacts that can be misleading. A widely used technique is the intensity derivative, or "shift-difference" algorithm which takes the value of the pixel at some specified direction and distance ("shift") from a pixel and subtracts it. The result is a map of intensity gradient changes in the direction of shift. A limitation of this method is that intensity boundaries aligned along the direction of shift do not show. To overcome this problem, we devised a shift-difference algorithm that involves both radial and rotational shift with respect to a specified point. Thus, the value of a pixel becomes;

$$DN' = [DN(x,P)-DN(x-dx,P-dP)] + [DN(x,P)-DN(x-dx,P+dP)],$$

where DN' = modified digital number of pixel
$DN(x,P)$ = original digital number of pixel
x = radial distance from specified point
P = position angle from specified point
dx = amount of radial shift
dP = amount of rotational shift

The result is analagous to unsharp masking except the "mask" is sharp and shifted spatially. The intensity gradients which have a spatial frequency larger than the shift are greatly reduced while the gradient changes occuring over the spatial regime smaller than the shift are greatly enhanced (Fig. 1).

Setting the specified reference point at the position of the nucleus (in practice, the point of maximum light), this algorithm facilitates studies of the dynamics of cometary atmospheres. The result of application of this algorithm is a map of production rate changes with time and direction. The optimum amount of shift for a particular image

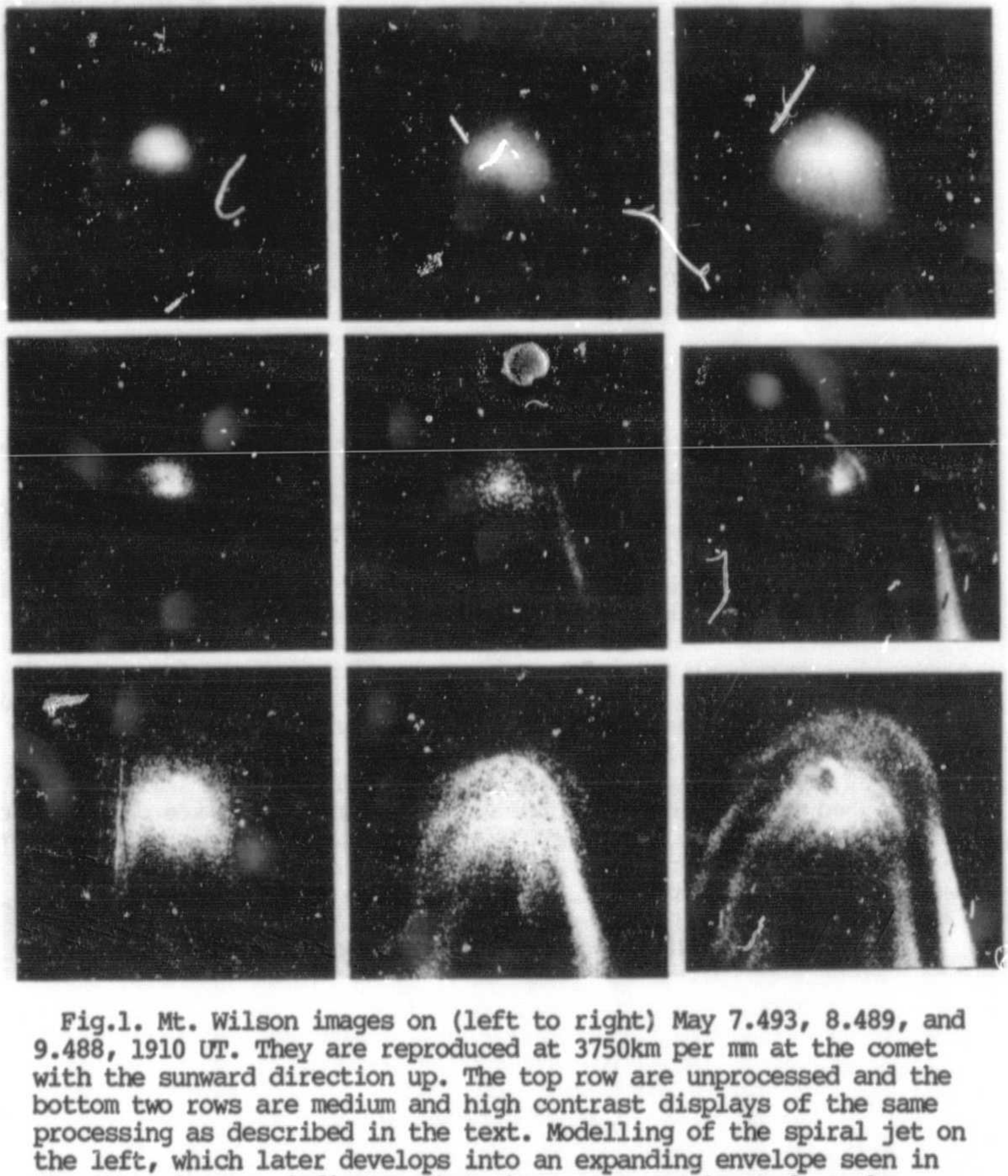

Fig.1. Mt. Wilson images on (left to right) May 7.493, 8.489, and 9.488, 1910 UT. They are reproduced at 3750km per mm at the comet with the sunward direction up. The top row are unprocessed and the bottom two rows are medium and high contrast displays of the same processing as described in the text. Modelling of the spiral jet on the left, which later develops into an expanding envelope seen in the other images, indicates that the source was located on the nucleus equator. Original plates courtesy of Mt. Wilson and Las Campanas Observatories.

depends upon the image's intrinsic signal-to-noise ratio, pixel size and characteristic feature edge dimensions. An emperical approach must be employed to find the optimum parameters for each image, and the result must be compared with the original plate to ensure that processing artifacts do not appear.

REDUCTION

All of the 1910 plates were guided on the comet (but not always with the desired precision). To obtain accurate plate scale and orientation, faint field stars were measured and used as secondary references relative to SAO stars as measured on the Palomar Sky Survey plates. The plates were digitized with the array edge parallel to the plate edge, and the point of maximum density at the center. Accurate plate scales and orientations, and positions of Halley's center of light were obtained. The comet's positions were compared with Yeomans' osculating orbit to check for possible errors in the recorded exposure times. Except for one case, the residuals were within a few arcsec and randomly distributed in sign across and along the orbit track. We found no systematic displacement of the point of maximum light with respect to the ephemeris position. All positions were measured with an internal movable cursor in the display system.

Photometry from the 1910 photographs is very difficult because of the absence of any sensitometric calibration. By comparing images taken in succession with different exposure times, and making assumptions about stable sky conditions, consistent development and similar reciprocity failure and storage conditions, it was possible to reconstruct the emulsion's characteristic curve and convert the digitized image to relative intensity units. Since opportunities to obtain the needed pairs of images were very rare, all of the processed images were kept in density units.

Emphasis is being placed on accurately recording exposure times and calibrating field orientation and plate scale for images obtained by the NNSN in 1985-86. When photographic images are being made, sensitometric calibration should permit relative photometry to 2-5%. For CCD imaging through the standard IAU comet photometry filters, standard star calibrations should permit 1-3% absolute photometry as well.

COMA FEATURE CHARACTERISTICS

A strong jet, whose photographic density could be converted to relative intensity units, was compared to the coma background to determine the increase in dust density. The jet (the vertical loop seen on the May 9 image in Fig. 1)was 15-30% brighter than the background coma at the same distance from the nucleus. The contribution of C2 and CN (corrected for atmospheric absorption and losses in optics) were accounted for to ensure that only dust was being measured (Larson and Sekanina, 1984). Assuming that the depth of the jet along the line of sight was similar to the observed width, the actual particle number density in the jet exceeded the surrounding coma by several tens of times. The presence of one of these jets in the line of sight to the nucleus may produce significant contrast attenuation of the nucleus as seen from a spacecraft.

The processed images show, for the first time, the evolution of coma features over several days. As previously pointed out (Sekanina and Larson, 1983; Larson and Sekanina, 1984; Sekanina and Larson, 1984), these features begin characteristically as spiral jets which "unwind" from the nucleus and develop into expanding envelopes in the outer coma on the following days. A particularly good example of this is seen in the processed images taken on May 7-9 from Mt. Wilson (Fig.1). This pattern was shown to be diagnostic of continuous dust emission from a discrete source on the rotating nucleus. However, interpretation is often complicated when the low optical depth coma features overlap.

The characteristic motions of the coma features indicate that they are composed of dust ejected from the nucleus and moving under the influence of solar radiation pressure. The measured projected expansion velocities range from 0.2-0.4 km/sec. A computer program was written to model the motions of particles of various sizes (and therefore of different radiation pressure cross sections) emitted continuously from a source on a rotating nucleus. Given initial conditions of ejection, it is possible to study the coma structure with time (Fig. 2). The initial conditions depend upon the nucleus spin vector and the terminal ejection velocity distribution of the particles. Constraints, based on the (prograde) sense of rotation indicated by the nongravitational perturbations of the comet's orbit, and on the direction of spiral jets observed from different directions have led to a nucleus spin axis orientation that

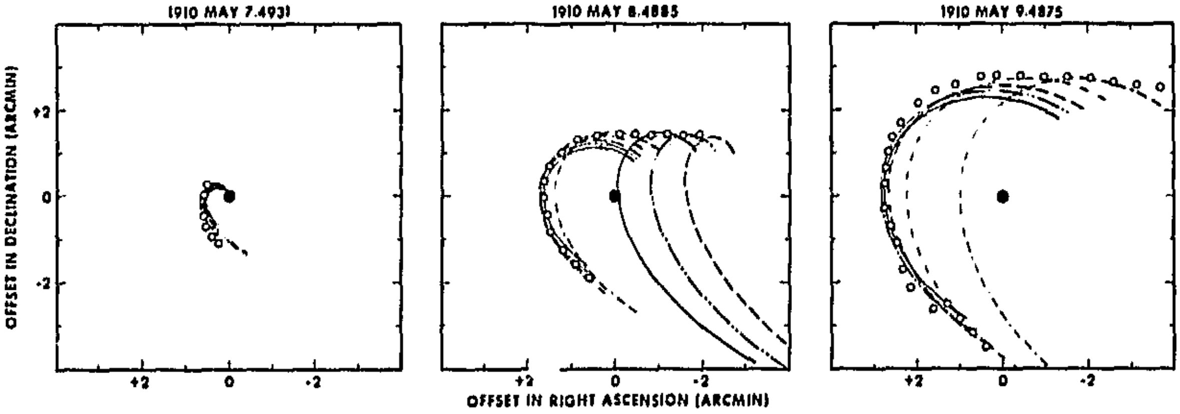

Fig. 2. Model plots of the prominent jet shown in the Fig. 1 series. North is up and east is to the left. The open circles are points along the feature boundaries measured as offsets in declination and right ascension from the point of maximum brightness (large dot at center). The curves represent loci of particles subjected to different radiation pressure accelerations from the sun (which was at position angle 75 degrees). The good quality of fit is demonstrated by the high degree of correspondence between the observations and the envelope to the particle loci. The feature is composed mostly of smaller particles. Fits such as these to jets at different times and viewing geometries strongly constrain the orientation of the nucleus rotation pole.

was consistent with that determined from observed feature motions (Sekanina and Larson, 1984). The north pole is inclined to the orbit plane by 45 degrees and points toward RA = 1.3 hr, Dec = -27 deg. The shapes of the spirals are indicative of a rotation period longer than one day, but quantitative models of the individual features could not constrain the period to better than about 0.4 day. Our current nominal period of 1.73 (0.4) days should be refined by modelling more features in 1910, and may further be revised with the 1985-86 data.

Additional modelling of other features will also result in a map of active emission areas on the nucleus in 1910. Asymmetries or clustering in the global distribution of emission areas may be responsible for the lightcurve variations observed in 1984, and may provide some insight to the internal structure of the nucleus.

The modelled jets indicate that they are active only when the sun is above the local horizon. Typical ejection velocities are in the range 0.3-0.5 km/sec, and particle sizes range from 1-10μm in radius.

FUTURE PROSPECTS

This study indicates that there will be much to record and observe with long focus imaging during the 1985-86 apparitions. Rapid image processing and modelling will be used on the groundbased images to locate emission areas on the nucleus surface to aid interpretation of spacecraft imaging.

The success of this effort will depend strongly upon the acquisition of high resolution images a few times per day during the favorable periods of observation in 1985-86. Experience with the 1910 plates and modern imaging capabilities suggests that the period when the comet is approximately within one Astronomical Unit of the earth and/or the sun (November 3,1985 - May 10,1986) and when the moon and sun are not interfering, will be the prime observing period during which diagnostic coma features may be observed. Since the presence of strong, measurable jets and envelopes is unpredictable, we are encouraging observations throughout this prime observing period as well as the designated IHW days. Because it will not be feasable for NNSN observers to observe continually throughout this period, observers of the Astrometry Net may consider taking longer-exposure plates whenever possible to record coma structure. Such exposures may, on occasion, prove critical. Filtered red sensitive plates that reduce the contribution of gaseous emission bands and improve the contrast of the dust (continuum) are recommended. Exposures should not be too long so as to saturate the nucleus condensation since that is a prime reference point. The exposures must be well guided to compensate for the comet's motion. Observers in the Astrometry Net who would be interested in contributing to this work are encouraged to contact the authors for further details and assistance.

This work is carried out jointly by the Lunar and Planetary Laboratory, University of Arizona, and the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We received assistance from many people in obtaining the 1910 photographs, using the KPNO PDS microdensitometer, and the various computer facilities. J.S. Gotobed (LPL) implemented the image processing algorithm on the Space Telescope VAX 11/780 computer at KPNO, and D.K.Yeomans (JPL) provided osculating orbital elements for the relevant epochs.

REFERENCES

Bobrovnikoff, N.T. 1931. Halley's comet in its apparition of 1909-1911 Publications of the Lick Observatory. 17, 305-482 pp.

Larson, S.M., and Sekanina, Z. 1984. Coma morphology and dust-emission pattern of Periodic Comet Halley I. High-resolution images taken at Mount Wilson in 1910. Astronomical Journal. 89, 571-576 and 600-606 pp.

Perrine, C.D. 1934. Observaciones del Cometa Halley durante su aparicion en 1910. Resultados del Observatorio National Argentino. 25, 1-88 and 99 plates.

Rahe, J.,Donn, B., and Wurm, K. D 1969. ATLAS OF COMETARY FORMS, NASA SP-198 (U.S. GPO, Washington, D.C.), 128 pp.

Sekanina, Z.,and Larson, S.M. 1983. Rotating comets: Development of dust spirals into envelopes. Bulletin of the American Astronomical Society. 15, p. 651.

Sekanina, Z.,and Larson, S.M. 1984. Coma morphology and dust-emission pattern of Periodic Comet Halley. II. Nucleus spin vector and modelling of major dust features in 1910. Astronomical Journal (in press).

Recommendations

Frontispiece from the 1668 **Cometographia** by Johannes Hevelius.

On the left is an allegorical figure of Aristotle, who is demonstrating his view that comets are sub-lunar, terrestrial phenomena, and on the right is a figure representing Kepler explaining his view that comets are celestial objects moving along rectilinear paths. The central figure is Hevelius himself demonstrating his theory that comets are celestial bodies traveling on curved trajectories near the Sun.

OMIT
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RECOMMENDATIONS FOR COMETARY OBSERVATIONS

UNIFORMITY (Provision of a homogeneous data set)
1. Use the shortest useful exposure that is consistent with a good signal-to-noise ratio.
2. It is preferable to expose many images, but only the best one or two positions per night should be reported.
3. A red filter is preferred.
4. It is recommended that a bulk purchase of plates/film be made (2415 or 098-04 emulsion).

QUALITY CONTROL (Only well made observations are useful)
1. Observers should be critical and reject suspect observations.
2. Use grating as appropriate.
3. Good tracking is required (preferably on the comet rather than on the stars).
4. Measure UTC times of exposure start and stop times to one second.
5. Carefully follow established photographic procedures.

DOCUMENTATION (Required for evaluation of observations)
Observations should include:
observer's name
telescope used and its location
image scale
sky/weather conditions
subjective assessment of image quality
problems encountered
nuclear/total magnitude (but only if reliable)

RECOMMENDATIONS FOR ASTROMETRIC PLATE REDUCTIONS

1. Use at least twice as many reference stars as there are terms in each coordinate (ie., 6 stars for linear reductions with astrographs and long-focus reflectors, 12-15 stars in the case of observations with Schmidts.
2. Avoid reductions using only three stars.
3. Measure the point of peak brightness and aim at exposing so that the image of the comet is one magnitude above the threshold.
4. Reject dubious images.
5. Use a least squares plate constants method, rather than dependences.
6. Give topocentric (not geocentric) B1950 positions, generally with the UTC time given to 0.00001 day, R.A. to 0.01 seconds of time and Dec. to 0.1 second of arc.
7. Do not make corrections for elliptic aberration.
8. If measurements are being made by the bisection method, take both direct and reverse readings, with the target both first and last; for the automatic scanning method, it is sufficient to record the readings in one direction.

RECOMMENDATIONS FOR DATA SCHEDULE AND DATA FORMAT

Desired Data Schedules

Comet Halley: During the interval October 1, 1985 through March 1986, data should be reduced and transmitted to the orbit determination center within 48 hours if possible. During other periods, data should be transmitted within one month of the observation times.

Comet Giacobini-Zinner: During the interval July through September 1985, data should be reduced and transmitted to the orbit determination center within 48 hours if possible. During other periods, data should be transmitted within one month of the observation times.

Recommended Data Format For Transmission To Orbit Determination Center

It is recommended that astrometric data sent to the orbit determination center include the name of the object observed, the observer and observatory, the time of the observation, the right ascension and declination and supplemental information on the sky conditions, problem areas and magnitude information. The following format example is suggested for all Telex and electronic data communication systems;

```
P/Halley observations by N.S. Chernykh at Crimea Observatory
1985 10 28.00000  05 35 40.26 +21 30 00.0  095  Chernykh   1
1985 11  1.00000  05 22 16.50 +21 48 11.4  095  Chernykh   2

note 1: seeing = 2", m1 = 9.1
note 2: image diffuse with no central condensation
```

In this example the time (UTC) is followed by the right ascension and declination (1950.0), the observatory code and the observer. The observatory codes are listed in Minor Planet Circulars 4766 (dated 1979 July 1) and 7759 (dated 1983 March 28).

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Astrometric Observations

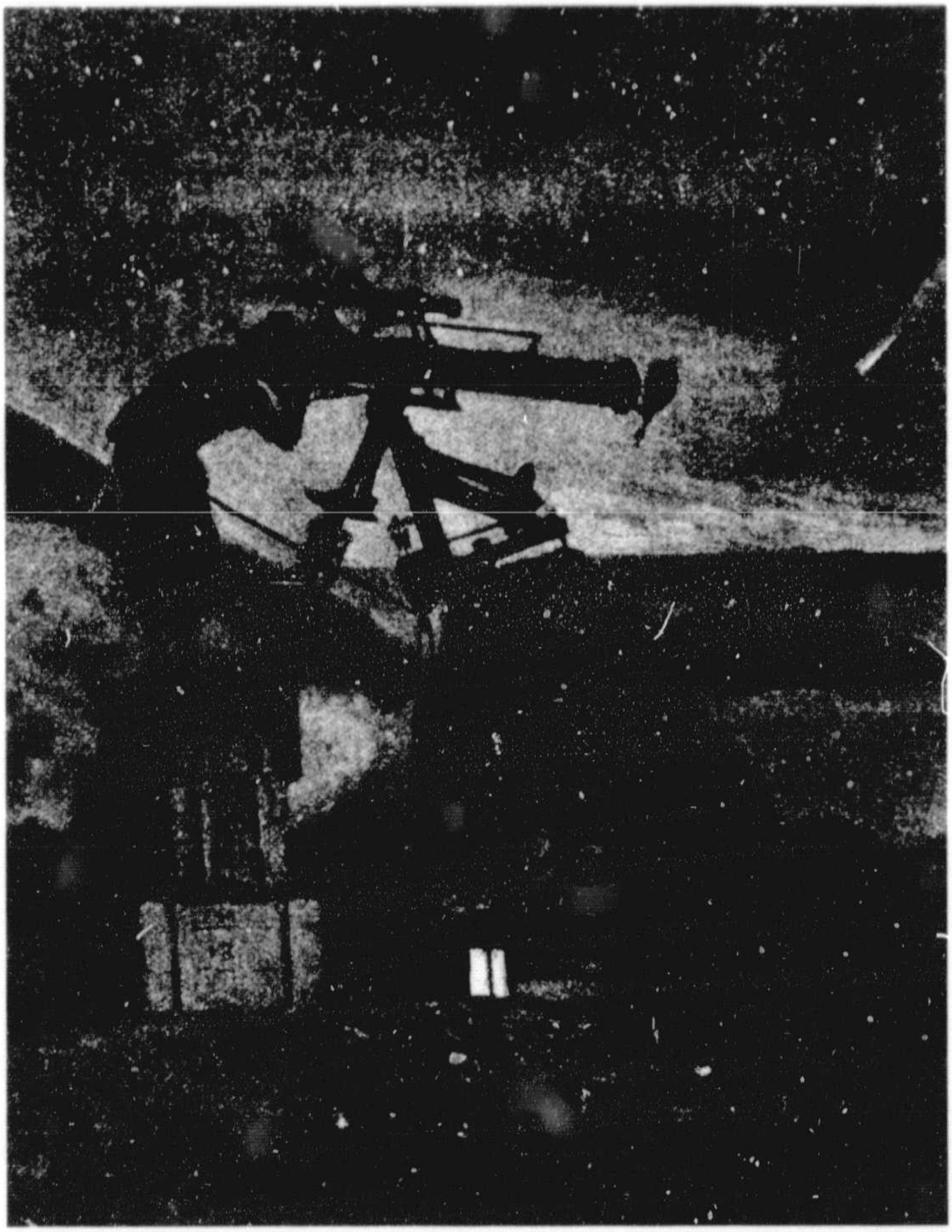

Illustration showing Jean Mascart observing
Comet Halley on May 17, 1910.

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REMARKS ON COMETARY ASTROMETRY

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ABSTRACT

A statistical examination of the astrometric observations made during the past 20 years indicates that there are generally sufficient data on bright and well-publicized comets. On the other hand, astrometric coverage of fainter objects has recently become a severe problem. In spite of an increase in the number of participating observatories, fewer observatories are making significant contributions. Automated methods have generally improved the quality of observations. The timely communication of observations is also discussed.

QUANTITY

From time to time we have bemoaned the current lack of astrometric observations of comets. It is certainly true that, since 1978, when the practice of publishing large numbers of observations on the IAU Circulars was terminated, publication then being relegated to the MPCs (an abbreviation for both Minor Planet Circulars and the complementary title Minor Planets and Comets), the number of available astrometric observations has significantly decreased. This decrease is very obvious if one makes a comparison with the situation during the years immediately preceding 1978.

The removal of the bulk of the nonurgent observations from the IAU Circulars had become a necessity. Transfer to the MPCs had an added advantage in that the automatic data-handling procedures of the Minor Planet Center facilitated the collection of cometary astrometric data in machine-readable form, and subscribers who have purchased the magnetic tape of observations of minor planets will find that the tape also now includes a substantial amount of cometary data. It was in fact our aim that the cometary data be complete back to 1964, although there are many earlier observations in the collection too.

Statistical Analysis

A brief analysis of the more than 15,000 cometary astrometric observations collected during the past 20 years is perhaps of some interest. Dividing the observations chronologically into three equal groups gives break points near the beginnings of 1973 and 1978, so the number of observations reported during the past six years is comparable to that during the previous five years; but it took nine years to accumulate as many observations before that. These figures cannot be exactly correct, because many of the pre-1978 observations not published in the IAUCs have been omitted, particularly observations that were in error by more than a few seconds of arc, as well as cases for which references could not easily be found when the file was constructed from a more haphazard collection accumulated in connection with our studies of cometary nongravitational forces and of the extent of the Oort Cloud. Since the transfer to the MPCs there has been an attempt at completeness, with observations frequently being reprinted from other journals, although hopelessly incorrect observations are still excluded from publication (or republication). Any error in the count is obviously therefore in the sense that the number of pre-1978 observations is too low, which serves to enforce the deterioration since 1973-1977 and suggests that the current situation is not really any better than during the 1960s.

<u>Best observed comets</u>. A more detailed chronological breakdown would obviously be influenced by the occasional appearance of spectacular or well-publicized comets. The 12 best observed long-period comets and the number of positions reported of each were as follows:

1973 XII	Kohoutek	854
1970 II	Bennett	548
1977 XIV	Kohler	433
1975 IX	Kobayashi-Berger-Milon	387
1983d	IRAS-Araki-Alcock	348
1969 IX	Tago-Sato-Kosaka	328
1982 VI	Austin	287
1970 XV	Abe	282
1978 XXI	Meier	278
1976 VI	West	276
1973 II	Kojima	271
1966 V	Kilston	230

The above list indicates that observers now respond to a conveniently observable comet at least as well as they ever did. In spite of its splendid appearance in the middle of the well-covered interval, our host's comet 1976 VI, in tenth place, was after all a morning object--as was the sungrazer 1965 VIII (Ikeya-Seki), for which the file could drum up only 129 positions. The third entry (1977 XIV = 1977 m) in the above list is perhaps a bit of a surprise, but this comet was conveniently observable in the evening sky in the northern hemisphere in the early autumn. That same interval in 1977 (a few months before the transition to the MPCs) also yielded the best observed single apparition of a short-period comet, the discovery apparition of P/Chernykh (1978 IV = 19771). In this category the 12 leading comets were:

1978 IV	P/Chernykh	234*
1976 XI	P/d'Arrest	226
1978 XIV	P/Ashbrook-Jackson	200
1983n	P/Crommelin	183
1978 XI	P/Wild 2	174*
1982 VIII	P/Churyumov-Gerasimenko	161
1972 VI	P/Giacobini-Zinner	151
1982j	P/Tempel 1	132
1969 VI	P/Faye	117
1982k	P/Kopff	113

1983j	P/IRAS	102*
1980 XIII	P/Tuttle	91

The asterisks denote discovery apparitions, and the fourth entry (which will certainly rise to first place when all the data are collected) again shows what a little publicity can do. It also would appear that there is not much wrong with the effort during the last few years.

Poorly observed comets. On the other hand, there are also a lot of only moderately bright and downright faint comets, as often as not morning objects and frequently located in inconvenient parts of the sky. If one considers the number of observations per cometary apparition, he gets a very different picture. Only sixty-eight objects received Roman numeral designations during 1973-1977, but there were 94 during 1964-1972. The observations from 1978 onward are of as many as 111 further cometary apparitions. There have been 55 cometary apparitions at which fewer than ten astrometric observations were made, and except for the faint IRAS discovery 1983f they have been exclusively of short-period comets, in six cases of short-period comets at their crucial discovery apparitions. The single observation by T. Seki in Japan of P/Encke as it approached its recent perihelion passage has now been augmented with a post-perihelion pair from A. C. Gilmore and P. M. Kilmartin in New Zealand, but the situation is clearly far from satisfactory when one considers that the comet was conveniently-enough placed that amateur astronomers were able to make frequent visual magnitude estimates. Since Elizabeth Roemer terminated her observing program in Arizona at the end of 1976 coverage of many of the returning short-period comets has significantly deteriorated. It is all very well that observers can be motivated to try to recover objects of widespread interest like P/Halley and P/Giacobini-Zinner (the latter because of the ICE mission) while they were around magnitude 24, but nothing has ever been done with comets in magnitude range 21-23. And whereas Elizabeth Roemer came to describe many of her recoveries of comets at magnitude 20 as routine, we are frequently hard-pressed now to get unequivocal recoveries of comets when they have brightened to magnitude 18. It is increasingly happening that recoveries are in fact made in the course of programs of physical observations of comets, and some of the alleged recoveries (not always announced in the IAU Circulars, however) in this way have clearly referred instead to minor planets that just happened to be in the vicinity.

Observed arcs and observation density. The termination of the Arizona program has also affected the span of time covered by the observations of a comet at its first apparition. Only nine comets of the recent period have been followed or will be followed for as much as a year. This compares with 13 during the intense stretch, which as already noted contained a much smaller total number of comets. The median density of observations of a new long-period comet is 0.5, one observation being made during every two days. The four most densely observed comets were:

1970 I	Daido-Fujikawa	2.67 obs/day	(12-day arc)
1979 X	Bradfield	2.19 obs/day	(75-day arc)
1983d	IRAS-Araki-Alcock	2.18 obs/day	(160-day arc)
1978 VII	Bradfield	2.06 obs/day	(35-day arc)

Twelve returning short-period comets had an observation density greater than the long-period median, although only the five cases with a total of ten or more observations have any significance:

1976 XI	P/d'Arrest	0.68 obs/day (332-day arc)
1983n	P/Crommelin	0.67 obs/day (272-day arc)
1982j	P/Tempel 1	0.56 obs/day (234-day arc)
1969 VI	P/Faye	0.53 obs/day (220-day arc)
1972 VI	P/Giacobini-Zinner	0.52 obs/day (288-day arc)

The point is, not that these cases are so great, but that the observation density for the bulk of the comets is so abysmal. The density for P/Crommelin will presumably decrease if anyone should succeed in making an observation after 1984 May 7.

Participating observatories. During the span 1964-1972 the number of different observatories participating in astrometric observations was 95. The number increased to 109 during 1973-1977, and since 1978 there have been as many as 119 observatories. Before one gets too encouraged by the increase, he should note that, whereas the median number of observations per observatory was 17 and 18, respectively, during the first two spans, since 1978 half of the observatories have produced no more than ten observations apiece. Furthermore, some observers have a nasty habit of producing half-a-dozen or more observations of the same comet on a single night. This is an absolutely useless procedure. The optimum number of observations of each comet at a single observatory on a given night is very definitely two; one may be sufficient for an experienced observer, but the check offered by a second observation always inspires more confidence. The two observations should be independent, not just measurements of the ends of a single trail. Some 20 percent of the observatories are responsible for 80 percent of the observations. Up to 1972 half of the observations were made at 7.4 percent of the participating observatories. During the intense middle span 9.7 percent contributed half of the observations, but in the recent years the proportion has dropped to only 6.4 percent. Only two observing programs have produced more than 500 observations during any one span, namely, the Arizona program and B. Milet's program at Nice, each during the first span; and only one program, that of A. Mrkos at Kleť, consistently yielded more than 400 observations during each of the three spans. Programs (identified here by MPC observatory code) yielding more than 100 observations during one or more span rank in each span as follows (and it might be said that, for the most part, these leading programs do in fact not produce unnecessary extra observations of the same comet on a single night):

Code	1964-72	1973-77	1978-84
012	12	7	
020	2	12	
022			11
029		15	
035	8		
046	3	1	1

056	6	14	
095	5	9	15
210	11	8	
323	9	2	3
370/372	4	5	8
415			14
474/485		6	4
491			12
657			9
675			6
688		13	7
689/691/693	1	4	
707			13
801		3	2
805		11	10
809		10	5
821	10		
822	7		
885		16	

It should be remarked that codes 370, 372, 415 and 885 refer to strictly amateur astronomers; and that codes 657 and 707, which have both been playing an increasing rôle in cometary astrometric work during the past two or three years, involve professional astronomers using their own equipment. By combining the observations from more observatory codes it can be seen more clearly that an increased load is being put on amateurs, particularly groups in Japan and the U.K. While one certainly does not want to belittle some of the very important amateur contributions, and it is undoubtedly true that there would be more of them if suitable measuring equipment were more widely available to them, amateurs are clearly magnitude and resolution limited in relation to professionals. Funding agencies and telescope-user committees in western countries should be made aware of this fact if the situation with regard to coverage of faint and difficult comets is not to get even worse than it is now.

QUALITY

But quantity counts for absolutely nothing if observations are not accurate. Automated reduction methods have of course become steadily more prevalent during the past 20 years, many observers are applying checks done by only a few in the past, and more than 90 percent of the observations reported nowadays are of what might be termed adequate accuracy. The gross errors of the past have been largely eliminated, although it still frequently happens that observers are careless about recording the <u>times</u> (and even the dates!) of their observations. The wall clock in the dome of a professional telescope generally used for studies of galaxies may be wrong, but digital watches showing both date and time accurate to a few seconds a month are now widely and cheaply available, and unless clouds are severely hampering an exposure there is absolutely no reason why an observer should not be able to give the effective UT of his observation correct to within a few seconds.

Adequate positional accuracy can be defined as 2-3 arcsec, although a few observers regularly achieve an accuracy of 1-2 arcsec. Which star catalogue is used for the reduction does not seem to make a great deal of difference, provided the observer makes some effort to eliminate from the solution occasional stars whose proper motions differ significantly from what had been anticipated. One would like to believe that results using the special Halley Catalogue will be somewhat more satisfactory than those obtained using the Astrographic Catalogue, but an overexposed or underexposed cometary image will give a poor result anyway. The convenient SAO Catalog is the choice of most observers, but several use instead the AGK3 for northern-hemisphere objects. Comets that are very uncondensed are of course particularly troublesome, and while the IHW test run during the last week of March on P/Crommelin might be regarded as a success because the comet happened to be brighter than expected, it should be noted that most of the observations reported after mid-March that were of adequate accuracy were those obtained with the 1.2-m Schmidt telescopes in California and New South Wales.

COMMUNICATION

The IHW involvement with the Giotto mission is going to require that the first post-perihelion observations of P/Halley be measured, reduced and made available within a matter of hours. Cometary astrometrists nowadays make their measurements with a wide variety of equipment and differing degrees of automation, but it should be considered unsatisfactory if the reduction of the final position of a comet takes more than a few seconds after the actual measurements have been completed. Cometary astrometry differs from stellar astrometry, and even to some extent from asteroid astrometry, in that observations published years after the observations are actually made are of very limited use. If there is an astronomer at a neighboring observatory, or even in a completely different part of the world, who is going to report a good pair of positions of a particular comet within 24 hours, to delay the measurement of your own near-simultaneous observations for several months merely means that you might just as well have stayed in bed! A printed list of observations appearing eventually in a so-called refereed journal may impress the director of your observatory, but immediate electronic transmission of the data from your computer to ours is infinitely more useful. In this respect I also want to remark that the oral communication of a series of observations by telephone is generally less satisfactory than communication by telex. With the possible exception of those critical final measurements made by the dedicated handful of observers who persist long after others have given up on a particular comet, the value of a particular observation diminishes very rapidly as time progresses: nowhere is this more apparent, of course, than during the first few days following the discovery of a new comet.

The measurement of less critical observations can be delayed, but the regular appearance of the moon provides a very natural cycle, and observers are encouraged to aim at the measurement of their remaining cometary observations on a timescale of a lunar month. Ever-increasing backlogs are discouraging to even the most hardy observers, and it can be noted that several cometary astronomers who also conduct even larger programs of observations of minor planets do in fact nowadays succeed in producing almost all of their astrometric observations essentially on a monthly basis. These monthly batches of observations should of course also be provided in machine-readable form if at all possible. Direct computer communication is possible but perhaps unnecessary for less urgent data, and the frequent mailing of full-length magnetic tapes containing only half a dozen observations somehow seems an example of overkill. Mini-tapes are convenient, and there has recently been some degree of standardization of both 8-inch and 5.25-inch magnetic diskettes ("floppy disks"). Punched cards may seem old-fashioned, but they are still a very convenient medium if up to a hundred or so observations are being transmitted at once. Punched paper tape, on the other hand, should nowadays be considered unsatisfactory. Optical scanners will presumably eventually become commonplace, but at the present time it is annoying if the only output from your computer is a bulky printout that has to be sent by mail and then keyed into our computer. And if you still have to type up manually for us your observations from your own computer output, the chance of a copying error is doubled.

Communication is a two-way street, however, and we are well aware that (in the absence of optical scanners) the uses of the mailed monthly batches of printed MPCs (and to some extent the IAUCs) are limited. As already noted, the Minor Planet Center's complete collection of observations of comets and minor planets is distributed on magnetic tape from time to time. Thought has been given to making the monthly batches of MPCs available in machine-readable form, but until there is more standardization of magnetic diskettes (for example) this would be prohibitively expensive. A computer dial-in service allows users to acquire the IAUCs and to extract orbital data from the MPCs (and to calculate their own ephemerides), but it is currently inconvenient (if not impossible) for subscribers outside North America to utilize this service. It is certainly to be hoped that during the next few years there will be dramatic improvements in the way subscribers can utilize, on an ongoing basis, the data collected by and processed at the Minor Planet Center.

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COMETARY ASTROMETRY WITH SCHMIDT CAMERAS

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ABSTRACT

The techniques used at the UK Schmidt to observe and derive astrometric positions of Comets are described.

INTRODUCTION

A great many of the professional comet discoveries are made using wide field Schmidt telescopes. In particular the Palomar Schmidt, the ESO Schmidt in Chile and the UK Schmidt at Siding Spring Observatory in Australia. The wide field of view and fast f ratio are two of the distinctive features of this design which make it attractive for comet work. The techniques described in this paper refer to those in current use on the UK Schmidt. However in large part the methods described may be applied quite widely.

THE UK SCHMIDT

The UK Schmidt is a classical design with a clear aperture of 1.24m and a focal length of 3.07m. The plate size is 356mm square giving a field of view of 6.6 x 6.6 degrees and a plate scale of 67 arc seconds per mm. One unusual feature is the corrector which is an achromatic cemented doublet allowing image widths at half maximum intensity of better than one arc second at all photographic wavelengths.

The UK Schmidt is engaged in a number of systematic surveys of the southern sky and most of the cometary work has been confined to faint comets, largely accidentally photographed, or follow-up plates on comets discovered by staff members. However, we have been closely involved with the many IRAS comets and previous to this had completed a major new asteroid survey in conjunction with Caltech.

The section following gives a brief discussion of the various stages in observing and reducing a comet observation.

THE PLATE FILTER COMBINATION

The principal aim is to produce a sharp well-defined image of the comet nucleus with optimally exposed reference stars. This is seldom easily attained in practice, depending to a large extent on the nature of the particular comet. At the UK Schmidt our choice of emulsion is fairly straightforward.

1) IIaO(blue), IIaD(visible) - relatively coarse grain but no hypering necessary. Stellar magnitude limit is about 21.

2) IIIaJ(blue-green), IIIaF(red) - fine grain but fairly elaborate gas hypering is necessary to obtain useful speed. Stellar magnitude limit is about 22.5.

3) IVN (near infrared) - fine grain but requires elaborate wet hypering. Stellar magnitude limit is about 19.5.

Our first choice for astrometry is always the IIIaF or IIIaJ since we have a well organised production line for fully hypered IIIa plates and their fine grain and good speed make them preferable to the IIa emulsions. The choice of filter for astrometry would depend on the comet magnitude but in general we use a GG495 filter combined with the IIIaF emulsion giving a 200-nm passband. For brighter comets we would probably use a GG455 with a IIIaJ plate giving a passband of about 85nm. The IIIaF/GG495 produces a sky limited plate in about 25 minutes.

We have carried out some experiments using Kodak 2415 emulsion on glass but there does not seem to be any particular advantage over our standard IIIa emulsions, at least in terms of speed.

One of our problems during the Halley run will be one of cost. We anticipate taking many exposures and since each plate costs nearly $100 before hypering, the expense of an unlimited observing program will be prohibitive. We are therefore investigating the possibility of multiple exposures on one plate using a limited but discrete area for each. With the extensive reference catalogue available for Halley a circular field of view of 2 degrees should be more than adequate for precise astrometry, or indeed most observations before the tail becomes extensive.

A rotating aperture wheel currently being designed for another project can probably be adapted for this use allowing up to six quite separate exposures on one plate. This system could easily be arranged to take consecutive exposures using different filters as long as the same emulsion can be tolerated ... for example in polarimetry or narrow-band interference work where emission band and nearby continuum are being examined. For photometric purposes a series of exposures on one plate undergoing the same conditions and processing has significant advantages, as well as reducing the number of plates to be processed.

The time taken between exposures is also considerably less allowing one to look for short term variations in structure. While it is possible to do a series of astrometric exposures on one plate without such an elaborate set-up, each observation is not strictly independent because of minor plate and emulsion deformities.

For those interested in photometric work we have a wide range of full-size broad-band filters and many special narrow-band filters ranging from 125mm square to 250mm square.

OBSERVATIONAL METHODS

In general most astronomical telescopes track at sidereal rate, although it is possible to do good astrometry on comets with a stationary camera such as the satellite-tracking Hewitt Schmidts, used recently during the close approach of IRAS-ARAKI-ALCOCK.

Until March 84 all comet plates exposed on the UK Schmidt were tracked at sidereal rate thus producing good stellar images but a trailed comet image. Thus one is faced with the task of producing precise astrometry using overexposed reference stars and a faint trailed comet image. One cannot determine the start or end of the trail to high accuracy although the mean position is normally better. The image is generally nebulous, especially at high magnification. On our local measuring machine the reference stars virtually fill the field of view and restrict the degree of magnification which may be used. Because the star images are overexposed the central image is too large to easily bisect on cross-wires and one must use the diffraction spikes as the positional reference. When one is making a deliberate attempt to photograph a comet, then a technique known as gating may be used to improve measurability. In its simplest form this means taking two exposures separated by a period of time thus producing a gap or gate in the trailed comet image. Indeed I would recommend gating on all normal routine exposures as well, since asymmetric gating allows one to determine the direction of motion of unexpected comets or fast asteroids and will improve their measurability. If one wishes to use automatic equipment to identify and measure large numbers of asteroids then a gated image is easier to recognise while the stellar exposure is unaffected by the method. It is very much easier to determine the precise position of the gate than the end of a trail because of image symmetry. However, the faintness of the comet image and the brightness of the reference stars remain a problem. In the case of Halley with its specially produced reference catalogue this will be less severe since the reference stars are much fainter than the standard catalogues.

During the Crommelin run, as well as astrometry, we also wished to obtain high resolution images and this was only possible if some method of tracking the comet were available. Although the UK Schmidt is equipped with a sensitive electronic autoguider it cannot function on an extended 12th magnitude image. It is possible to guide manually on a bright guide star and make manual offsets during the exposure to allow for comet movement. However, this is a technique which requires some skill and a great deal of practise to perfect and even then would not do justice to the optical performance of our Schmidt.

The UK Schmidt has two 254mm-aperture guide telescopes fitted with electronic autoguiders. They have the facility to offset their field centre from the camera axis by up to plus or minus half a degree. The movement may either be performed manually or using stepping motors with a step size of about 0.2 arc seconds. However, there was no facility to control these motors in the manner required to track a comet and this had to be built at short notice during the Crommelin run. The first lash-up functioned quite well being based on a Commodore PET personal computer and only the essential software routines.

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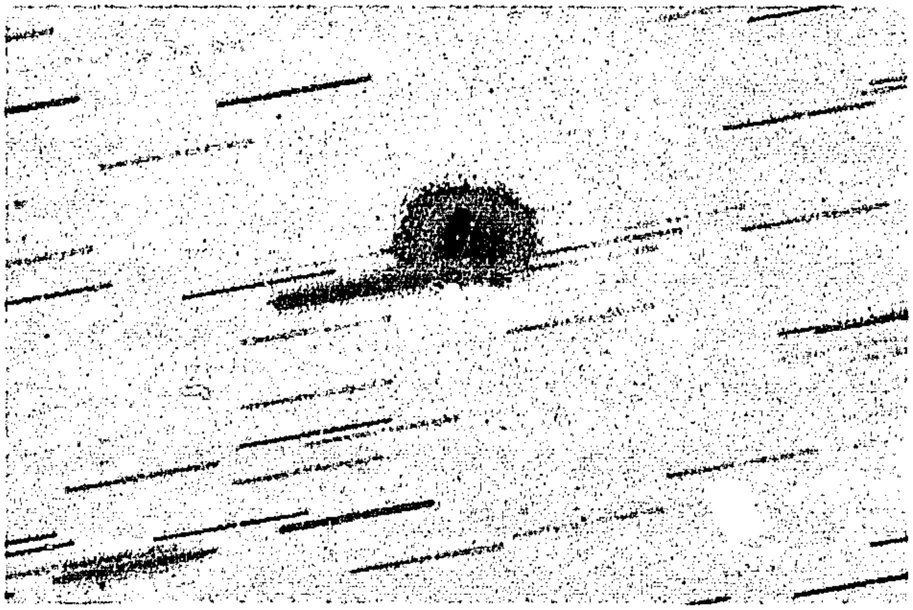

Comet Crommelin - tracked and gated - Plate VR9146

We were then in a position to obtain excellent cometary images at the expense of trailing the star images. However, since the star images are reasonably bright and much better defined than the comet image this is not a problem. The gating technique must still be used since the same setting difficulty applies to trailed star images. A number of gating options are possible depending on the apparent comet velocity. If the comet is slow moving then one can take a long exposure followed by a gap and then a short exposure while tracking at the comet velocity during the entire period. The length of the total exposure is chosen to optimise the comet image while the short exposure is chosen to give adequate stellar images which are not unduly trailed. If the comet is fast moving then even a short exposure may give excessive star trails. In this case it is possible to make a composite exposure at two rates. First one takes a comet exposure tracking at the appropriate velocity. The tracking speed then reverts to sidereal rate and after waiting an appropriate period for the comet image to move away from its previous position on the plate, with the shutter closed off course, a second exposure is taken to produce the positional references for the first images. The second technique is more complex and will seldom be used in practise.

PROCESSING AND STORAGE

The processing of large plates, while maintaining photometric uniformity and emulsion stability, is difficult, and requires great care (ref 1). No special precautions are taken for astrometric plates since the processing techniques used ensure that all plates remain essentially free from random emulsion distortions. Our plates are stored in an air-conditioned room beside the measuring machine, although the humidity is not controlled. This remains fairly low, in general, at Siding Spring. In high humidity climates some degree of humidity control may well be necessary.

MEASUREMENT

The equipment in use at the UK Schmidt is a custom built X-Y measuring engine with digital readout to 2-micron resolution. The original machine built to a design by J.G. Bolton has just been recently upgraded to improve its performance. Tests suggest that it is now capable of an accuracy of about 0.5 arc seconds or better although this is somewhat limited by the reference catalogues presently available. Before the machine was upgraded our standard error was quoted as 2 arc seconds although under favourable conditions we probably achieved closer to 1 arc second. We have found that there is no obvious improvement gained by using more than 10 stars providing these are fairly close to the comet image. In normal circumstances the main source of error is inherent in the difficulty of setting on the comet image itself. I have noticed references to people using an ink blob to mark the comet image since it presumably disappears under high magnification. I would consider this a dubious practise and best avoided. I would instead suggest that by reducing the magnification of the viewing microscope one can obtain equivalent or better accuracy.

REDUCTION

The reduction method uses a conventional least squares technique and optionally allows for radial distortion. The coefficients are determined from the reference stars and are not preset. The general upgrading of our system is also intended to include a rewrite of the software. The new version will certainly include preset coefficients since a better fit should then be possible with fewer stars. The current program produces an rms error of about 2.4 arc seconds when requested to fit 30 stars distributed evenly over the plate on the assumption that the Schmidt focal plane can be perfectly represented by standard coordinates. When allowance is made for radial distortion this drops to about 0.6 arc seconds. This is very close to the anticipated catalogue errors, which is surprisingly good as I would expect rounding-off errors to start to appear as the number of stars is increased. The program currently runs on a 32K Commodore PET microcomputer, whose numerical accuracy is limited to nine digits.

In most cases it is adequate to use the linear assumption when a limited area of the plate is being examined with the stars fairly close to the comet image. Indeed I have found it dangerous to try to determine the coefficients from a poorly distributed group of stars. The one exception to this is when the comet image is close to the edge of the plate. In this case it is imperative to use a fit allowing for radial distortion. In one case I was obliged to measure about 20 stars over the plate in order to get a reasonable position in agreement with positions from plates taken before and after.

If anyone is interested in copies of the software, then I would be quite happy to supply them.

Reference

1) Cannon, Hawarden, Sim, Tritton - Photographic techniques, Occasional Reports of the Royal Observatory Edinbugh (ISSN 0309 - 099X)

DISCUSSION FOLLOWING PRESENTATION

L.W. Fredrick: What are the effective passbands of the GG 495 + IIIF combination and the 2415 emulsion?

K. Russell: About 4900 to 6900 A in each case, but we have found the 2415 to be a factor of two slower.

N85-25021 D6

ASTROMETRY OF COMETS USING HYPERSENSITIZED TYPE 2415 FILM

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ABSTRACT

Kodak Technical Pan Film 2415 should be known to those doing cometary astrometry. It has exceedingly fine resolution (320 lines/mm) and, when properly hypersensitized, it is almost as fast as treated IIIa-J plates and reaches fainter stars. Reciprocity failure with the treated film is practically zero, and the shelf life of of treated film sheets is about a month at 2° C stored in a nitrogen atmosphere. This film is readily available in 4 by 5-inch sheets and is inexpensive. The film base is Estar, a plastic chosen for its stability. Over 120 astrometric measures of negatives on this film have shown a median residual error in comet positions of 1.1", a value that compares favorably with those of most observatories reporting positions.

DESCRIPTION

Fig. 1 shows a picture of selected area 57 with visual magnitudes of stars marked. The bright star at the center is SAO 82672, magnitude 8.1, 13h 06.3m, 29° 39' (1950.0). The magnitudes are from a table by Chiu, 1980, and were determined mostly by I. R. King, using plates from Lick, Palomar, and Kitt Peak observatories. There are 18 stars from 20.0 to 20.9 magnitude, and 6 from 21.0 to 21.2. The negative was made on type 2415 film. However, the most remarkable fact about the photograph is that it was taken with a 16-inch (40--cm) reflector.

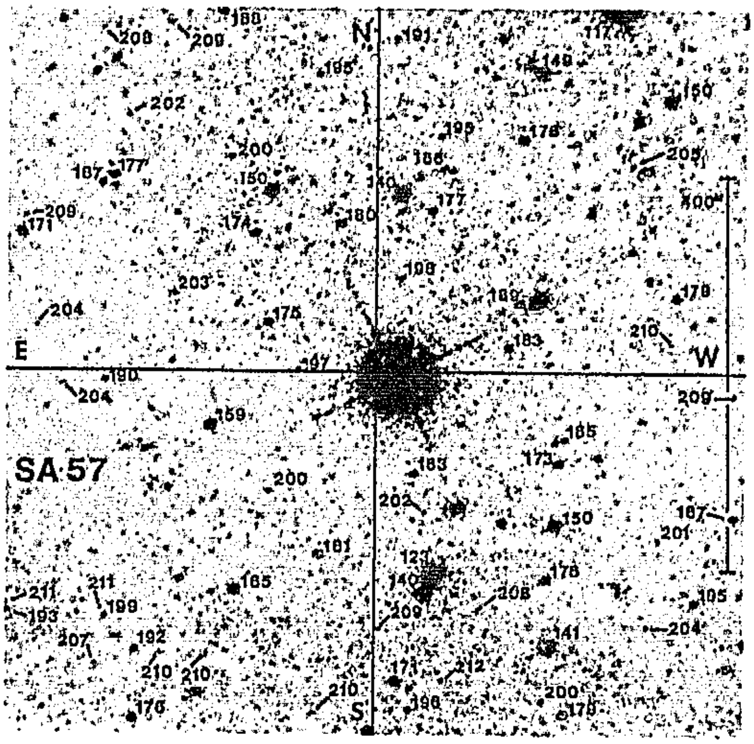

Fig. 1. Selected Area 57

This result is possible because the grain of the film is fine and the seeing disk is resolved on the film in the small telescope's image plane. Thus the limiting magnitude is determined by signal-to-noise ratios in the emulsion, as has hitherto been true only for very large telescopes. All sizes of telescope would profit by using this film, which has 5x the resolution of 103a-F plates and almost 2x the resolution of IIIa-F plates.

Without hypersensitization the 2415 emulsion is too slow for astrophotography. The earliest technical paper on hypersensitizing the emulsion was by Everhart, 1980, who found gains of 8x in speed and almost no reciprocity failure in the treated film. His recommendation is baking at 60°C, first an hour in vacuum, then 5 hours in 8% forming gas. (8% hydrogen, 92% nitrogen). A careful test on the reciprocity failure was made by A. G. Smith, 1982b. He found this failure to be almost non-existant over a range in exposures from 3 seconds to 2 hours. His preferred treatment is baking at 67°C, an hour in vacuum then 2 hours in pure hydrogen. The forming gas treatment seems to be substantially equivalent to the pure hydrogen treatment, and is much safer regarding explosion and fire.

Smith, 1982a, made careful measurements of the absolute sensitivity of type 2415 film in comparison with IIIa-F plates, the two emulsions having comparable color sensitivities. (A blue-sensitive version of 2415 is not available.) The result is that 2415 is 1/3 as sensitive as heavily hypered, heavily fogged, IIIa-F, but is only 30% less sensitive than IIIa-F which is given the more usual moderate treatment. The answer from our experience is that exposures as long as 90 minutes at f/5.5 will give the best possible negative, but that an exposure of one hour at this aperture ratio is usually sufficient. Sometimes we stop the aperture f/7 to lessen coma in cases where the reference stars are not close to the center of the negative and where the comet is relatively bright, say 17th or 18th magnitude. In such a case 40 minutes at f/7 is enough exposure. With this fine-grain film, reaching limiting magnitude with exposures of reasonable duration requires a telescope of f/6.5 or faster proportions.

Among professional astronomers there is a reluctance to use film. They use glass plates for several reasons: (1) They believe the best astronomical emulsions are available only on glass plates; (2) Glass is more stable dimensionally and lies flatter in the focal plane; (3) They have always used plateholders. If one absolutely insists on glass plates, the 2415 emulsion is available on special order as Kodak special plate 153-01, subject to the usual delay of about two months, minimum order 36 plates, costing about $10 for each 4 x 5-inch plate. If they could swallow their inhibitions and be adventuresome they could buy a box of 50 4 x 5-inch sheets of 2415 off the shelf at their local film supplier for about 50 cents a sheet.

The prejudice against film because it does not lie flat in film holders in well taken though. A good plate holder is easy to make, whereas a precise filmholder is difficult to design and make and is not yet available commercially. It should use a partial vacuum to hold the film flat against a back plane. This involves running a small vacuum line to the filmholder. The rewards of being able to save so much on emulsion cost make the precise filmholder worthwhile.

The Estar film base is so stable that we have seen no evidence in the 'plate' constants of a stretch in the emulsion base. Larger film sizes than 4 x 5-inch are not in production. Kodak will make them on special order. The minimum order for 8 x 10-inch sheets is 27 boxes of 50 sheets each, total about $1500. Perhaps that is not so unreasonable if several observatories share an order.

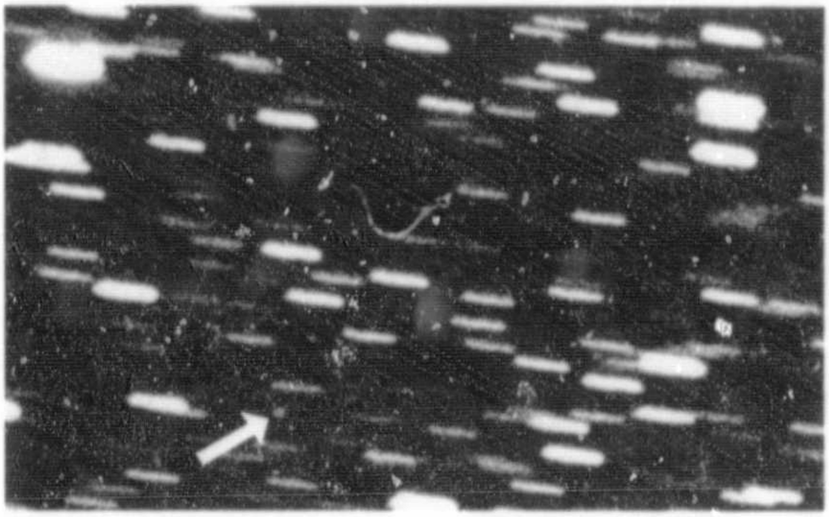

Fig. 2. The recovery photograph of Periodic Comet Taylor, 1983u. This was taken at our observatory on type 2415 film on Nov 3.40347 with the 0.4m f/5.5 Newtonian. Exposure 62 minutes. North is up. Bright star in upper left is SAO 114783. Comet is marked by white arrow. Comet's magnitude 19 to 20. The other spots on print do not look like comets, and in any case are not on the line of variation. Comet is found to be 0.94 day early. Everhart, 1983.

Another example of the use of this film is seen in Fig. 2. Would the performance of your telescope be improved with type 2415 film?

REFERENCES

Chui, L.-T. G. 1980. Classification of Stellar Population and Luminosity Classes for Accurate Proper Motions. Astrophys. J. Suppl. Ser. v44, p31-71. See table of SA 57 star magnitudes.

Everhart, E. 1980. Hypersensitization and Astronomical Use of Kodak Technical Pan Film 2415. AAS Photo-Bulletin No. 24, p3-6.

Everhart, E. 1983. IAUC 3889, edited by B. G. Marsden, Nov.15.

Smith, A. G. 1982a. Comparison of the Absolute Sensitivity of Kodak Technical Pan Film 2415 with Standard Astronomical Emulsions. AAS Photo-Bulletin No. 30, p6-8.

Smith, A. G. 1982b. Reciprocity Failure of Hypersensitized and Unhypersensitized Kodak Technical Pan Film 2415. AAS Photo-Bulletin No. 31, p9-12.

DISCUSSION FOLLOWING PRESENTATION

L.W. Fredrick: If you have a flat field, why not place a filter in front of the film and flatten it by a spring-loaded back?

E. Everhart: That would probably work.

L.G. Bowell: We have made tests on the astrometric integrity of film versus plates. Our basic result is that positions from film are fully as reliable as those from plates; residuals from reference stars are also comparable. However, I worry that there is a loss of sensitivity on film because of the thinner emulsion used. In the particular case of IIa-o, we noticed about a one magnitude difference between film and plates.

E. Everhart: Kodak films are different in this respect. I have heard that 2415 is better as a film than as a plate. Our 16 inch reflector has reached 21st magnitude on 2415 film.

D7

N85-25022

ASTROMETRIC PLATES OBTAINED AT THE PRIMARY FOCUS OF LARGE APERTURE REFLECTORS

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Coma, astigmatism and great differences in stellar magnitudes between the photographed object and reference stars constitute main sources of errors in measuring positional plates. All these three sources of errors can easily be eliminated by the method used at the Kleť Observatory for obtaining precise observations of faint objects by means of the 60 cm and 100 cm reflectors with focal lengths of 297 and 394 cm, respectively (i.e. by relatively very fast telescopes). The astrometric plates are taken by the method of two diaphragms.

The first diaphragm, with a small central aperture, is located in front of the photographic plate, this makes it possible to expose the object only with its closest area near the centre of the plate.

The second diaphragm is situated in front of the mirror, thus limiting the aperture to focal length ratio from 1:10 to 1:20, according to the requirements.

The photographic procedure is as follows:

When using the first diaphragm in front of the photographic plate, a comet or minor planet is exposed for the time necessary to obtain a measurable image.

Then the focal ratio of the mirror is reduced by means of the second diaphragm and the diaphragm with a small central aperture, situated in front of the plate, is removed so that the whole plate is exposed. By a very short (of the order of tens of seconds) exposure a sufficient number of reference stars can be obtained throughout the entire plate. The stars are very well defined to the very edges of the plate and are easy to measure.

Moreover, this method makes it possible to use plates of larger dimensions than usual so that it is always possible to find the necessary reference stars.

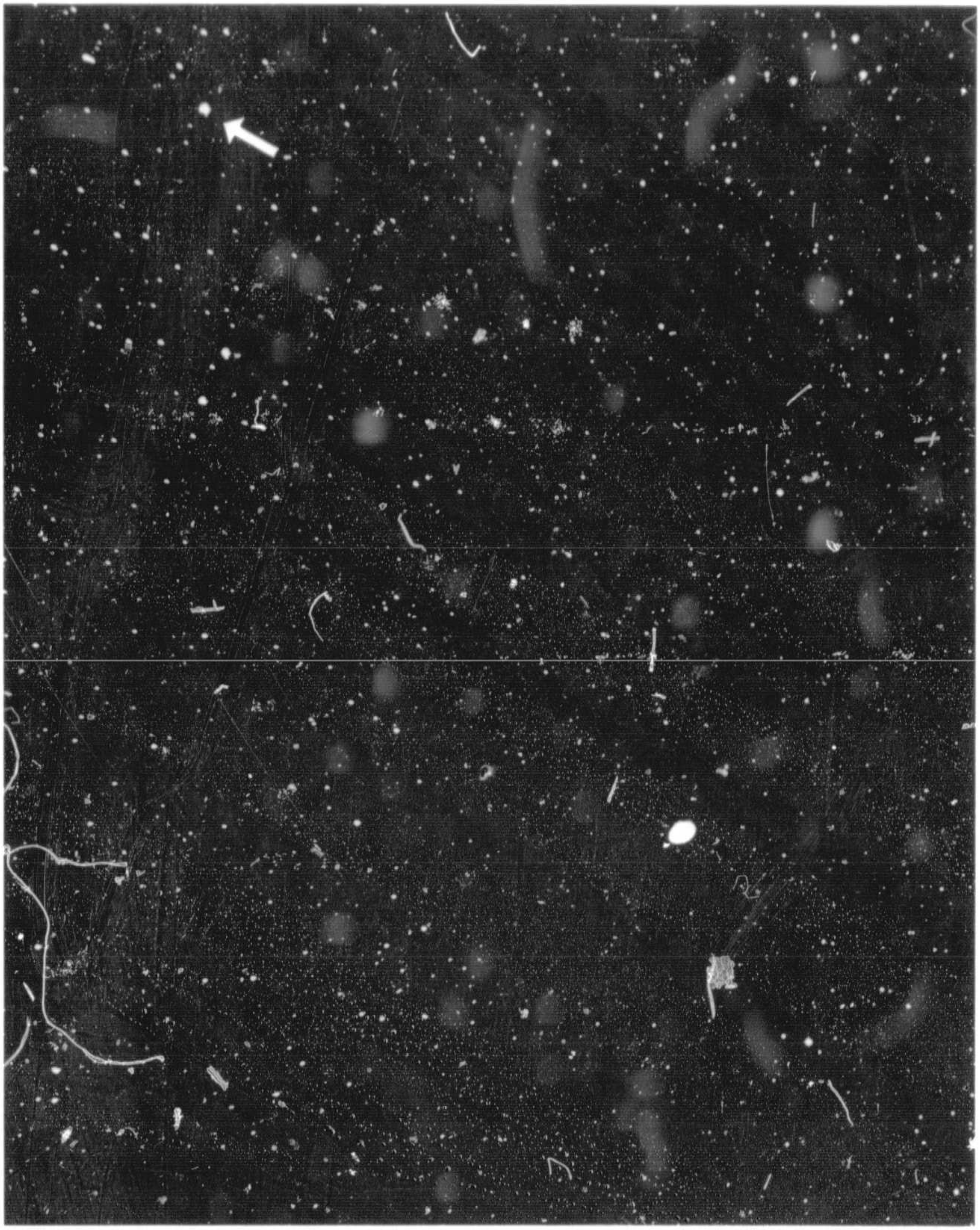

Fig. 1. Photo of the ring nebula in Lyra made by the 60cm mirror at the primary focus. The photo was obtained without diaphragms. Stellar images, deformed by the effects of comae are clearly visible at the edges of the plate.

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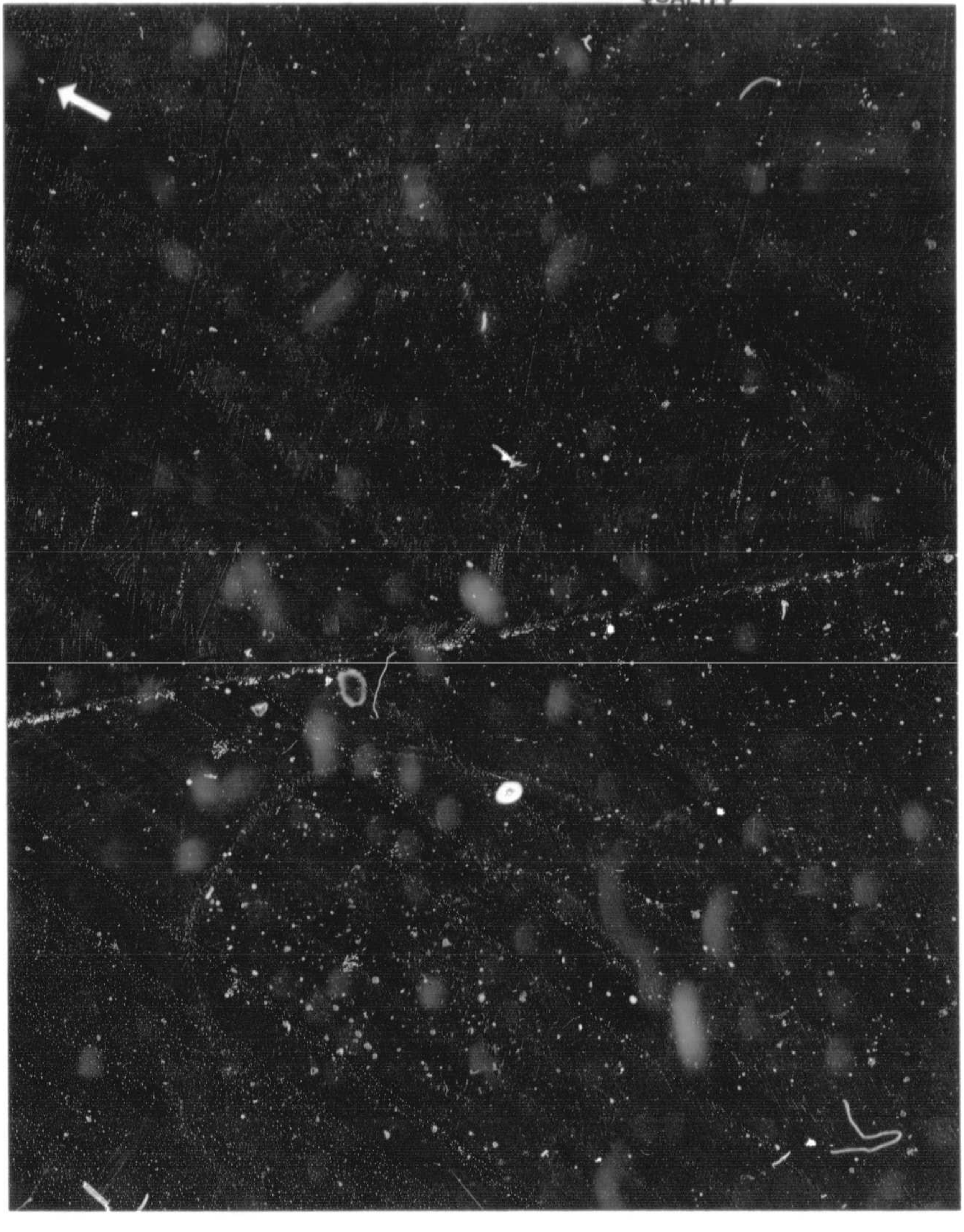

Fig. 2. Photo of the same object obtained using the two diaphragms. Stellar images are sharply defined, without deformations by coma or astigmatism, even at the edges of the plates.

D8

N85-25023

KITT PEAK MEASUREMENTS OF P/HALLEY POSITIONS

MICHAEL J. S. BELTON, Kitt Peak National Observatory, National Optical Astronomy Observatories, United States of America (NOAO is operated by AURA Inc. under contract to the U.S. National Science Foundation).

ABSTRACT

Techniques used for the acquisition and reduction of imaging data for astrometric positions of comet Halley at Kitt Peak National Observatory are described. These techniques are applicable to the comet while it is fainter than magnitude V~21. They yield positions that are uncertain by ± 0.9 arcsec. The reliability and consistency of the positions we have already derived could be improved by as much as a factor of four in a more ambitious astrometric program.

DATA ACQUISITION

The techniques we use are a response to the following difficulties:

(i) The comet is very faint;
(ii) The comet's orbital track on the sky is presently located in rich starfields near the galactic plane;
(iii) The instrumentation available for this work has limited dynamic range.

Because of the first two difficulties we have made great efforts to preselect the scheduled nights of observation by feeding the KPNO Telescope Allocation Committee only those dates for which there appeared to be little possibility of interference between the image of Halley and stars brighter than 20th mag. This was a substantial amount of work, since it entailed the accurate placement of the predicted track of the comet on enlarged prints of the Palomar Sky Survey (POSS). It has paid off, however, for another of our objectives - the acquistion of spectra of the nucleus. We (H. Spinrad, P. Wehinger, M. Belton, S. Wyckoff, D. Yeomans) have now obtained two such spectra while the comet was fainter than V~23.

We have used two cameras at the Mayall 4-m telescope on Kitt Peak to make photometric and astrometric measurements. Both cameras have solid state CCD detectors and their properties are indicated in Table I. Most of our data has been taken with the CRYOCAM and the properties of the TI

Table I. Cameras used in KPNO measurements of P/Halley

Focus	Inst	Detector	Read-Noise	Full-Well	Scale (arcsec/ pixel)	Pixel size (microns)	Format
			(electrons)				
4-m/Prime	--	RCA-CCD	~70rms	~120,000	0.58	30x30	352x512
4-m/RC	CRYOCAM	TI-CCD	~10rms	~20,000	0.84	15x15	800x800*

TI = Texas Instruments; RCA = Radio Corporation of America.
*Only 512x800 are used.

chip have determined our preferred mode of data acquisition. Our data is taken through one or another of a standard set of 'Bessell' BVRI filters available at KPNO (Bessell, M.S. [1976], P.A.S.P., 88, 557-560). The TI detector has the property of 'bleeding' charge both up and down columns from pixel sites that have become saturated. Moreover if the saturation is particularly intense then some of the charge will 'stick' in the detector and its effects will be seen for an extended time in many subsequent exposures, possibly affecting other scheduled observers. Examples of this 'bleeding' can be seen in Fig. 1 associated with stars as faint as mag V~16 in a 120 second exposure.

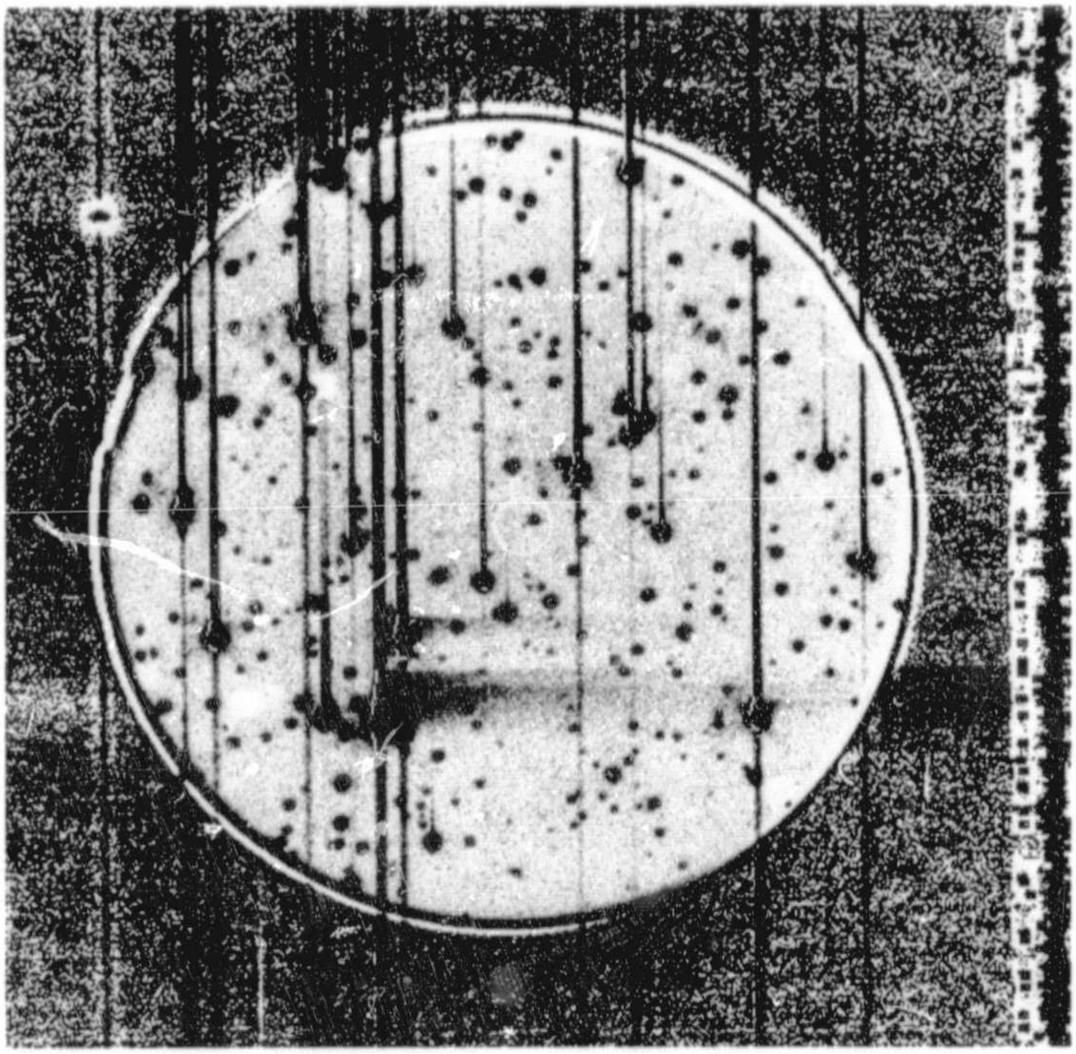

Fig. 1 A CRYOCAM frame of the P/Halley field taken on UT March 4, 1984 showing 'bleeding' columns. The image has been windowed and stretched to emphasize the problem.

The bleeding is nonlinear and is almost impossible to eradicate satisfactorily in subsequent image processing. By Murphy's Law these bleeding columns usually fall near to, or on, the image of P/Halley (or any other object of interest)! In principle some control could be obtained by rotating the camera on the telescope - but this option consumes precious observing time and we have avoided it. As a result of this problem we chose to acquire data in a series of short exposures guided at the diurnal rate. Alternatively we could have tracked the comet during the exposure but, as a result of problems with the telescope offset tracking capability, as well as complications in the data reduction, we decided to use the simpler strategy. Our exposure times are long enough so that the dominant source of noise is the sky background but short enough so that column bleeding and smear, due to the motion of the comet, is, for practical purposes, negligible. Most of our exposures are 120 sec during which time the comet moves (e.g. opposition, 1984) say, 0.8 arcsec (~ 1 pixel) on the sky. The seeing FWHM at KPNO is usually between 1.5-3.0 arcsec and so any blurring of the image of the comet due to its motion is not a pronounced effect. Fig. 2 illustrates the effects of blurring the comet image in the recovery data on P/Giacobini-Zinner which was obtained by Djorgovski, Spinrad, Will and Belton using a CCD camera at the prime focus of the Mayall 4-m telescope using the same techniques. At the time, P/Giacobini-Zinner was moving at a rate similar to those encountered with P/Halley.

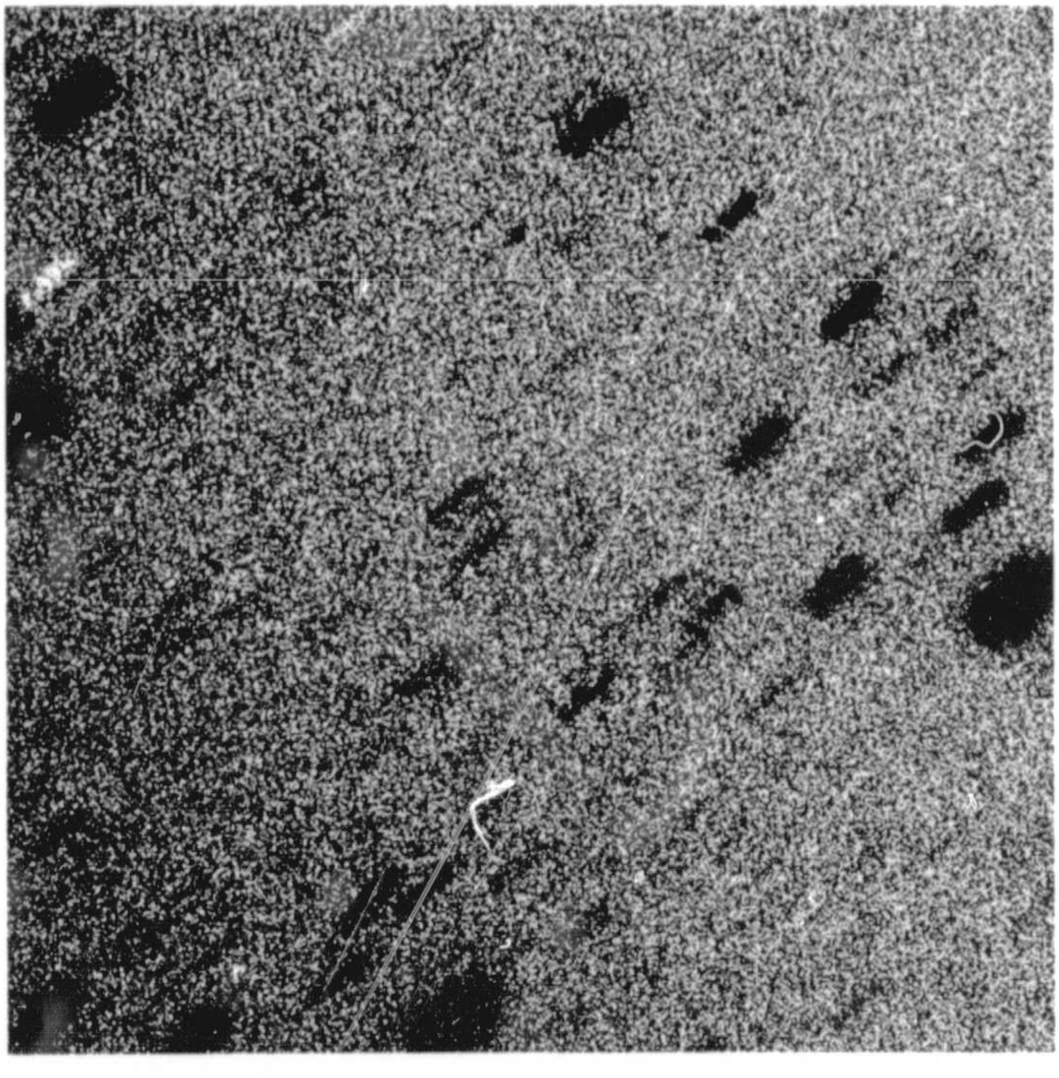

Fig. 2. P/Giacobini-Zinner showing slight smearing of the image during the individual exposures. This picture is a shifted sum of four 150 exposures. The data was obtained by Djorgovski and Spinrad.

General Properties of the Data

In 120 sec, under average seeing and dark sky conditions on Kitt Peak, the CRYOCAM will reach a limiting magnitude near V~23.5. A reasonable night can yield up to 50 or so exposures but it is our experience that only a fraction, roughly one half, of these provide useful data. The rest are compromised by faint stars that interfere with the P/Halley image. Unless most of the data on a particular night is compromised in this way such data is discarded. On the other hand if the majority of the data is so affected then we use a slightly more complicated data reduction procedure (described below) to recover the image of the comet.

DATA REDUCTION

Overall Scheme

(i) **Noise reduction process:** The raw images are first corrected for electrical bias. Fixed-pattern noise is corrected by ratioing the data with flat-field exposures of the inside of the dome. Residual vignetting in the field is removed through further ratioing to heavily smoothed images of a "blank" sky field. If necessary, any objectional stars present in the "blank" fields are removed by interpolation of the sky background into the region in which they fall. These operations, which result in a set of reduced, but uncalibrated data, are either done on the mountain the day following acquisition of the data, or at a later time using KPNO Interactive Picture Processing System (IPPS) and its standard software package.

(ii) **Calibration (a) Astrometric:** Approximately five stars in the predicted vicinity of the Halley image (which has usually not been identified at this point) that are bright enough to be measured on the POSS (V<20) are identified as secondary standards. The selection of suitable stars is constrained by the requirement that they be single with well defined images and in areas of the image that are not affected by 'bleeding' columns. The average separation of these secondary standards from the Halley image is roughly 40 arcsec.

The (x,y) pixel positions of these stars are measured in each Halley frame and checked for consistency. The measurements are done with a KPNO algorith called RADPROF and are repeatable to better than 0.1 pxl. If the telescope guiding system worked perfectly the positions of the stars would be identical in all frames. However, owing to refraction and flexure, the position of the standard stars in the individual Halley frames are generally found to drift over the period of observation and so a translational shift, (Δx, Δy), for each frame is usually applied that places the secondary standards in a consistent (x,y) reference coordinate system. The first usable Halley frame for the night is normally taken as the reference. The magnitude of these shifts changes systematically and may amount to a few tenths of a pixel during a night. While these shifts are small they are nevertheless significant if it is decided to use the ratioing technique described in the example below.

The secondary standards are located on the POSS plates and their equatorial coordinates (1950) are measured in the standard way. We use the KPNO Grant measuring engine and SAO stars as the primary positional reference. Approximately 10 SAO stars are used in each reduction and they are separated from the Halley position by up to 50 arc min. Computation, by least squares, of the linear transformations $(x,y) \rightarrow (\alpha\cos\delta, \delta)$ and $(\alpha\cos\delta\delta) \rightarrow (x,y)$ completes our astrometric calibration of the data. The rms residuals are characteristically two or three tenths of an arcsec in the positions of the secondary standards.

(b) Photometric. We use stars in NGC 2419 (R. Racine and W. E. Harris, 1975, Ap. J., 196, 413), and NGC 2264 (KPNO Video Camera Standards, C. Christian et al. 1980) to provide a photometric calibration. A single channel aperture photometry software algorithm on the IPPS is used to measure fluxes. The radius of the aperture used is usually set at twice the FWHM of the seeing disk.

(iii) Identifying Halley. With the astrometric calibration and Yeomans Halley ephemeris we predict the (x,y) position of the comet in each frame. These are then examined to see if the region around the predicted position is free of faint stars. If most of the data meets this criterion then the uncontaminated frames are shifted in the computer to take out the comet's predicted motion and then co-added. The summed picture represents our best defined image of Halley and its position can be estimated to about half pixel accuracy by making row and column line plots through the image. Frames in which the Halley image might be contaminated by a faint star, a defect, or some other object are discarded.

If the Halley image is compromised by faint stars in most of the data we pursue a different reduction strategy, which maintains astrometric precision but causes a loss of photometric precision. In this case, the individual frames, which have been shifted to remove the effects guiding drifts, are co-added to provide the basic reference frame. The positions of secondary standards are measured in this summed image and the astrometric calibrations are derived from it. In this summed frame, Halley, if it could be seen, would be an interrupted trail on the sky with a signal amplitude diluted by roughly the number of frames in the sun.

Each individual Halley frame is then ratioed to this reference, shifted to take out the comet's motion, and then co-added. The resulting "ratio" image has most of the signal associated with stars and galaxies removed, while the image of Halley emerges and its position can be measured in the way described above. This technique has the advantage that flat-fielding and fixed pattern noise removal is automatic. The drawback is that the photometric integrity of the resulting Halley image is reduced.

A Specific Example

To illustrate these techniques we use observations taken on 1984 UT March 4 with the CRYOCAM. The prognosis for this night was good in that no stars were expected on the predicted Halley track down to the limit of the POSS. A sequence of fifteen 120 sec exposures through the Bessel V filter were obtained. Because of 'overhead' in the observing procedure this 1800sec of exposure took 3300sec to acquire, not including calibration data. Thus the 'overhead' rate is unfortunately very high for our observing strategy.

Two stars were used to estimate the effective drift of the guiding system. Corrections of up to 0.228 pxls in x and −0.125 in y were applied to the individual frames. The astrometric calibration was based on five stars whose positions were measured in a summed version of all the frames. The RMS residual of the calculated positions of the secondary standard stars relative to their positions calculated from the POSS was ±0.24 arcsec. The absolute (Epoch 1950) coordinates for the secondary stars were based on a grid of SAO stars. The computer outputs for this night have been misplaced but usually 10-15 stars are used and the RMS of the residuals is about ±0.7 arcsec. This is clearly the major source of positional error.

The pixel scale was found to be 0.865 arcsec/pxl in x and 0.862 arcsec/pxl in y. Yeomans ephemeris was used to predict the position of Halley in each of the frames. A 19.7 (V) magnitude star (barely, if at all, seen at the limit of the POSS) and its ~23rd mag. visual companion were found to irretrievably compromise all but the last 8 frames of data (cf. fig. 3).

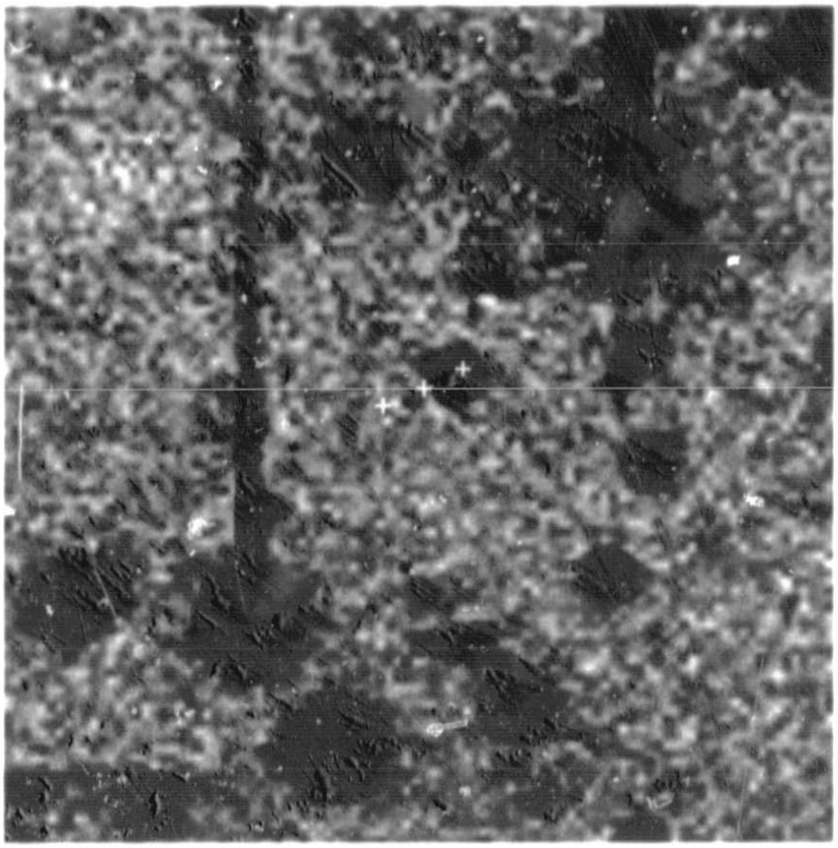

Fig. 3. P/Halley field for 1984 UT March 4. The visual double at the center of the field compromised the Halley image for most of the night. The + signs map out the track of Halley during the observational period. The comet moved from right to left in this representation.

In this data the comet could be just discerned (with difficulty and imagination) in the combination of at least two of the individual frames and its mean, but uncertain position was (x,y) = (255.25, 395.5) in pixel coordinates. Because of the interference from the background stars the ratio technique, described above, was used for a final reduction. The result is shown in Fig. 4. A slight residual depression can be seen in the region of the trailed 19.7 mag star. Fainter stars are effectively removed, and the image of Halley becomes clearly apparent. Its position, measured by making x and y plots cutting through the data was (x,y) = (255.5, 396.0).

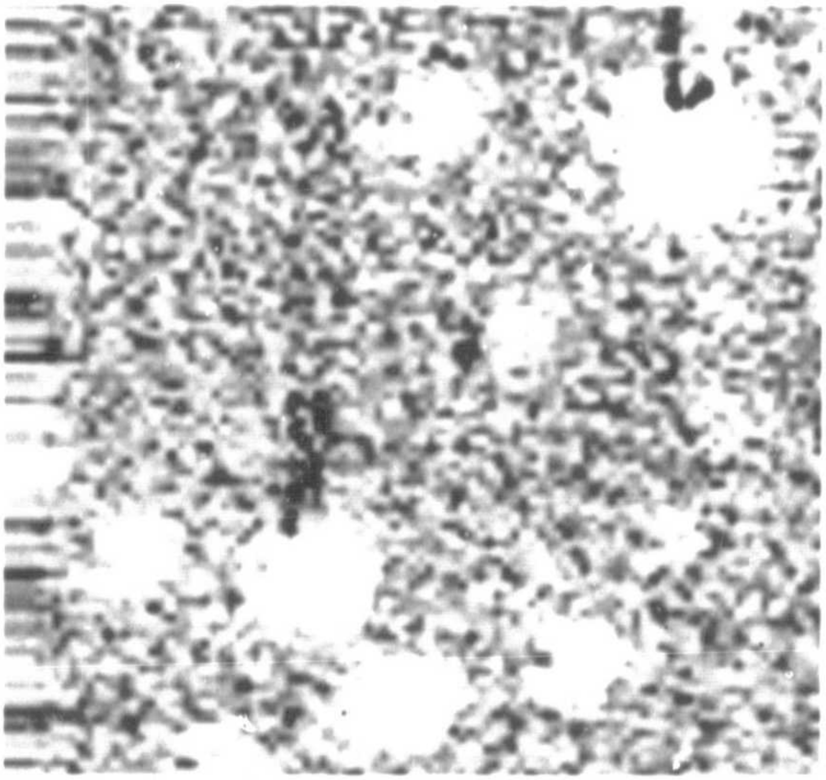

Fig. 4. 'Ratio' version of Fig. 3. The image of P/Halley can be easily seen near the center of the picture. The 19.7 magnitude star and its fainter companion have been nearly cancelled out in the ratio process.

Advantages, disadvantages

The techniques we use seem to have the following advantages compared with the classical method of tracking a comet during an exposure:

(i) Good control on reference star positions.
(ii) Photometric reductions with standard software.
(iii) Ability to edit data and minimize influence of faint background stars.
(iv) Availability of the ratio technique which can enhance the visibility of moving object in crowded fields.

The disadvantages include:

(i) Large observing overhead.
(ii) Considerable increase in data reduction effort

Data summary and errors

All of our astrometric and photometric results to date are collected in Table II. We have, at present, data for 2 more nights which has not yet been reduced. Possible errors in a single position are estimated as follows: There is an uncertainty of approximately ±0.5 pxl in the location of the Halley image (±0.5 arcsec for the CRYCAM and ±0.3 arcsec for the RAC); there is a further uncertainty of about ±0.3 arcsec in the position deduced from the secondary standard grid; finally there is an uncertainty of roughly ±0.7 arcsec in the positions of the secondary standard stars themselves as gauged from the residuals of the primary SAO standards. Exactly how to combine these errors is not clear, but since we have used a relatively large number of SAO stars we expect the main errors to be in the secondary star calibration and the direct measurement of the Halley position. Thus errors of about ± 0.9 arcsec RMS may occur in our position estimates.

TABLE II. SUMMARY OF KPNO POSITIONS

Date	Instrument	Observers*	α(1950) (h:m:s)	δ(1950) (o:':")
1982 Oct. 18.3866	CRYOCAM	B & Bu	07:10:53.38	09:31:11.7
1982 Oct. 20.3854	CRYOCAM	B & Bu	07:10:43.22	09:29:18.5
1982 Dec. 13.2059	CRYOCAM	B & Bu	06:56:26.31	09:03:17.7
1983 Feb. 13.2107	RCA	B,W & Wy	06:29:44.53	09:55:52.1
1983 Feb. 13.2736	RCA	B,W, & Wy	06:29:43.20	09:55:57.5
1984 Mar. 04.2490	CRYOCAM	B,S,W, & Wy	05:57:18.12	11:41:43.4

*B=M.J.S. Belton; Bu=H. Butcher; W=P. Wehinger; Wy=S. Wyckoff; S=H. Spinrad.

Possible Improvements

There are a number of changes in our reduction procedure which clearly could improve the astrometric positions derived from our data. These are:

(i) Improved primary standards. The SAO stars are too bright and their POSS images are poor.

(ii) Correct for proper motion. We have not investigated or attempted this.

(iii) Use a larger number of secondary standards. This would require using stars further from the Halley image.

(iv) Use better astrometric reduction procedures on the secondary standards. We use the KPNO 'ASTRO' software (by D. Wells), which accounts for non-linearities in the transformations, only for the primary standards. We use a simple multiple linear regression program ΣMLRXY (Hewlett-Packard-41C) to calculate Halley's position since the secondary standards are so close to the Comet.

(v) Find a better way of estimating the position of the Halley image. It should be possible to get the errors to the ± 0.2 pixel level.

With these improvements the RMS errors could perhaps be reduced to ±0.2 arcsec.

ACKNOWLEDGMENTS

I would like to acknowledge the work, effort, and encouragement of my many associates in this endeavor, which started with the search for Halley

in the fall of 1977. The following people have worked with me on this project since that time. Sethanne Hayes, Art Hoag, Harvey Butcher, Pamela Melroy, Hyron Spinrad, Peter Wehinger, Sue Wyckoff, Ray Newburn, and of course, Donald K. Yeomans. Without the excellent ephemerides provided so freely and promptly by Yeomans we would all be still looking for Halley.

DISCUSSION FOLLOWING PRESENTATION

R.S. Harrington: It may not be worth the effort of going to 0.2" accuracy. Even if we can get the star catalog scatter that small, there is still the problem of the systematic errors in the fundamental star catalog system, which can be that large.

P.R. Weissman: As a general question for all the speakers this morning, how much does having a high precision ephemeris lead to a bias in data reduction or reporting of results? Is it possible that the reduction techniques, using predicted positions and motion, introduce a bias, or that excessively variant results fail to be reported?

M.J.S. Belton: The ephemerides only enter in through the predicted motion of the comet. This results in only second order effects in the derived positional accuracy. At Kitt Peak, we have not yet seen any excessively variant results.

D9

N85-25024

PROBLEMS AND PROCEDURES OF COMETARY ASTROMETRY

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These remarks are addressed to those observers who want to engage in a little bit of solar system astrometry-- most particularly P/Halley-- without making a career of it. I can't think of a way to make the task exciting, but I hope I can offer some practical suggestions that will make it easy and the results useful.

Photography of comets or asteroids for the purpose of astrometry requires consideration of a few details not met with in other astronomical problems. In the general case the object has a substantial non-sidereal motion and one must decide whether to track on the fiducial stars or on the object: one or the other will produce trailed images. In most cases the easier choice, sidereal tracking, is the wrong one. If the comet is faint one may need integration of the image; if it is bright an elongated coma tends to confuse the center of light and thus the presumed center of mass. In either case measurements of elongated images will be inferior to circular images. It is almost always true that the fiducial stars over-condition the plate constant solution, and one therefore prefers that the poorer measures be associated with the many stars rather than the single object.

The best method for introducing the required image motion compensation to the detector will depend on the focal plane facilities available. The easiest will be software corrections for those with appropriate auto-guiders. The clumsiest and most aggravating is a manual offset made in two axes of an x-y stage holding the detector or the guide eye-piece. For those without auto-guiders who intend to take more than a few exposures, I strongly recommend supplanting the manual system with an automatic offsetter consisting of a stepping motor to drive the lead screw of the stage and a control circuit to step the motor at discrete, selectable intervals appropriate for the comet's motion. I will supply details of a simple control circuit we have used, failure-free, for many years to those requesting it. In our case, the stepper drives the lead screw through a rubber chain-belt gear pair. In any case the motion of the stage should be no more than 0.1 arcsec/step. If the double stage has rotational freedom, only one such system is required.

MEASUREMENTS

The peculiarities associated with measuring elongated images dictate many of the observing procedures, so it is best to discuss the measurements first.

The eye does funny things, and if you are using yours to measure plates, always measure the plates both direct and reverse (i.e., rotated 180 degrees between measures). The average of these measures eliminates a personal bias.

If the object is an asteroid and the exposure has been made while tracking its motion, there is no problem in selecting the center of the image as the point to measure. For comets, it is often true that center of light of the inner coma is the easy and proper point to choose. In some cases a much smaller and brighter "nucleus" will be apparent and this will define the position well. Rarely, there will be more than one nucleus or the single nucleus will not correspond to the center of light of the inner coma. Measure and describe everything. Your observation has special value when combined with others and it is reasonable to expect those who have all the observations to untangle the ambiguities of complex cases.

The beginnings or ends of elongated star images do not provide good fiducial points, but the averages of these two positions do give the star position at mid-point of the exposure. (Purists will note that this is not strictly true, since the plate scale is not constant across the plate. The rest of us are glad to know that the error introduced is entirely trivial except in truly bizarre cases.) It is best to align the plate on the measuring engine so that the star images are parallel to, say, the x-axis. the entire image is then available for positioning the y-screw. The decision on how to position the x-screw depends both on the character of the image and on personal preference. Obviously one aims for a procedure that gives the measurer most confidence in choosing the same relative position when the star is to the left or right of the cross-hair. (The personal bias can be very strong here, making the direct and reverse measures mandatory.)

If the star images are comatic, it can be extremely difficult to choose those positions on a trailed star that would represent the core of the image at either end of the exposure. If you know your telescope well enough, it is worthwhile to make some mental correction for coma when setting on the trail ends. Of course users of your results should be warned that the fiducial stars were of poor quality.

OBSERVATIONS

The measuring problems demonstrate that one needs to place particular care on the beginning and end of the exposure. The mid-time of the exposure should be known to an accuracy equal to the time required for the comet to move 0.1 arcsec. It is good practice to record the beginning and time to within 1 sec, even though such accuracy is seldom needed.

Guiding errors are less harmful in the middle of the exposure than at the ends. Exposures can be extended beyond the planned time if necessary to assure good ends of images.

It is poor form to end exposures in an overcast or any seriously reduced transparency. Better to close the camera and hope for a clearing.

Any emulsion, and particularly modern emulsions that have been desiccated before sensitizing, lose sensitivity as they absorb moisture. In the worst conditions, the sensitivity can decrease by nearly a factor of two in 30 minutes. To avoid this bias between the beginning and end of trails, one should maintain the emulsion in a dry state with dry air or nitrogen during the exposure.

D/10

N85-25025

ASTROMETRY AT LA SILLA

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ABSTRACT

Astrometry of comets and minor planets is done regularly at ESO, La Silla, Chile. Plates are obtained with the 1 m Schmidt telescope and the 40 cm GPO, and CCD frames with the Danish 1.5 m telescope. Reductions are carried out by microdensitometer scanning and image processing at ESO Garching, FRG. P/Halley will be observed intensively during the interval from perihelion passage on 9 February 1986 until the middle of March 1986. "Almost real-time", accurate positions will be made in support of the spacecraft missions.

Keywords: Astrometry, minor planets, comets, P/Halley

1. INTRODUCTION

The European Southern Observatory was created by an international agreement in 1962, which also laid down guidelines for the establishment of ESO's research facilities. Five countries, Belgium, France, FRG, Netherlands, and Sweden signed the convention; they were later joined by Denmark (1968), Italy (1982), and Switzerland (1982). After intensive site testing, the 2400 m La Silla mountain, approximately 600 km north of Santiago de Chile in the Atacama desert was selected and since then 13 telescopes have come into operation at ESO. The site is among the best in the world with excellent seeing and well above 2000 clear hours per year.

The main reason for the establishment of ESO was to give the opportunity to European astronomers to carry out frontline astronomical research with large instruments from a good site. Until then, most of them had access to smaller telescopes only, the majority of which was situated at inferior sites near major European cities.

With the great expansion in astrophysical work which took place from 1960 onwards, it was natural that the ESO facilities were first of all oriented towards spectroscopy and photometry. Less weight was given to astrometry and only recently has this classical discipline become more active at La Silla. Positional observations are mainly made of solar system objects, i.e. minor planets and comets. No stellar astrometry is done at present.

2. ASTROMETRY OF SOLAR SYSTEM OBJECTS AT LA SILLA

Three instruments are currently used at La Silla for astrometric observations: the 1 m Schmidt telescope, the 40 cm double astrograph (GPO) and the Danish 1.5 m telescope.

The 1 m ESO f/3 Schmidt telescope went into operation in 1972 and ~ 20 comets and many hundreds of minor planets have been observed with it. Five new comets were discovered and several hundred new minor planets were identified. Most of the observations were made on blue sensitive plates (in particular Quick Blue Survey plates) and so far few solar system objects have been discovered on the red plates taken for the ESO (R) half of the joint ESO/SRC Atlas of the Southern Sky. In practice, the limiting magnitude for observations of solar system objects with this instrument is ~ 20. Observed positions have been published regularly in the MPC's since 1975. An investigation of the brightness of faint comets, most of which were observed with this instrument was made by West (1982). All of the Schmidt observations have been made by H. E. Schuster and reduced by R.M. West (ESO) and C. Lagerkvist (Uppsala, Sweden).

The 40 cm f/10 GPO has a field of 2°x2° and has been a rich source of minor planet discoveries after 1976, mainly by Debehogne (Royal Observatory, Brussels, Belgium) and his co-workers in Brazil, Sweden, and Italy. The limiting magnitude is ~ 17.

With the installation of a 320x512 RCA CCD at the Cassegrain focus of the 1.5 m Danish f/8.5 telescope, it has become possible to detect and make positional measurements of extremely faint objects. Past achievements include the early observations of P/Halley on 10 December 1982 and 14 January 1983 (West and Pedersen, 1983), the long series of astrometric and photometric measurements in January 1984 of P/Halley (Fig. 1) and the pre-recovery image of P/Giacobini-Zinner with a magnitude close to 25 (Fig. 2). This telescope also has a 16x16 cm plateholder at the Cassegrain focus; however, it is little used at the moment.

Schmidt and GPO plates and CCD frames are reduced at the ESO headquarters at Garching near Munich, FRG. The photographic plates are scanned with an OPTRONICS or a PDS 1010A two-dimensional measuring machine. The actual measurements of positions and intensities are carried out by means of the ESO Image Processing Systems, IHAP (HP 1000) and MIDAS (VAX 11/780); for details, cf. West (1981) and West and Pedersen (1983).

The experience shows that by measuring a substantial number of astrometric standard stars (e.g. ~ 30 AGK3, SAO or Perth 70 stars on a Schmidt plate), it is possible to achieve r.m.s. accuracies of the order of 0.3 arcseconds in both directions through global solutions with all quadratic and cubic terms.

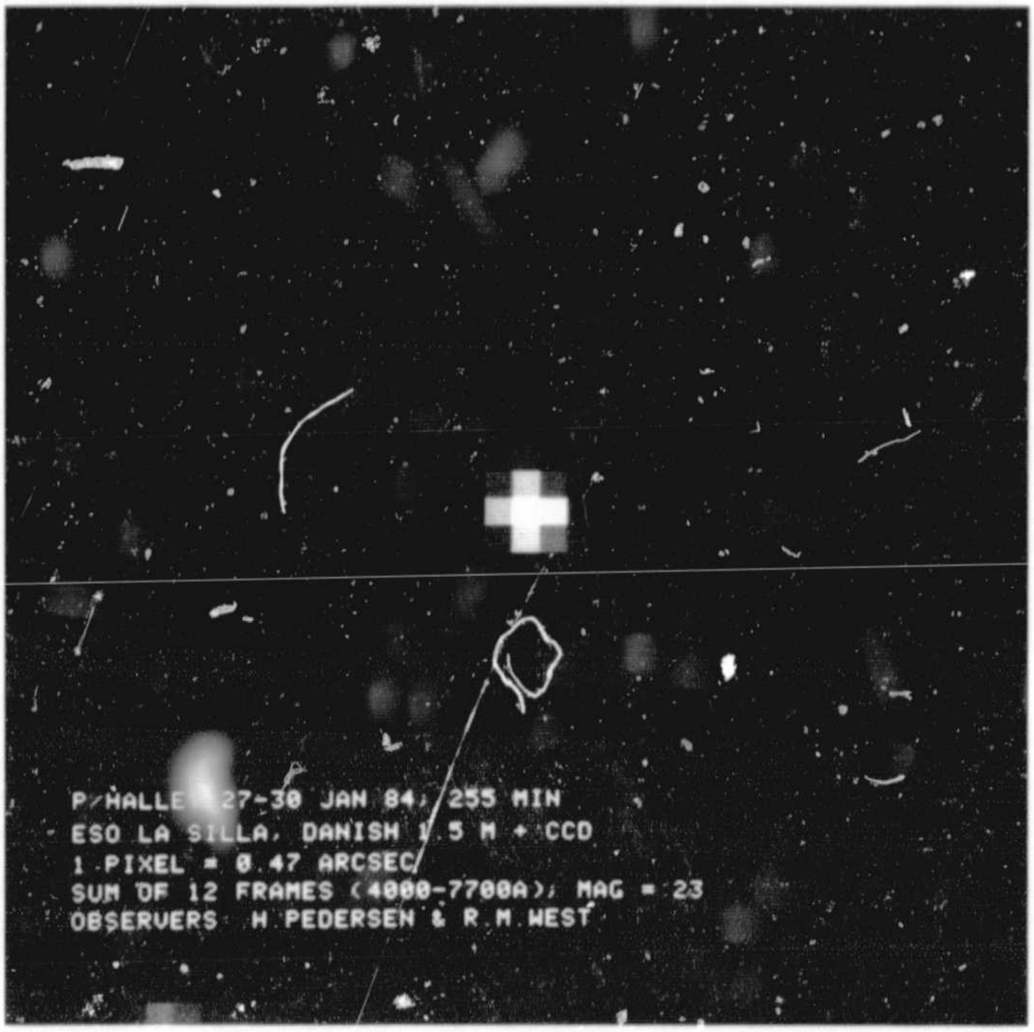

Fig. 1 Digitally added images of P/Halley, January 1984
From the absence of a visible coma, an upper limit of about 28.5 mag/arcsecond can be set on surrounding gas. It thus appears that no major outgassing has taken place.

Fig. 2 Digitally added images of P/Giacobini-Zinner
Three 30 min. exposures were shifted according to the comet's motion. The image has a very small s/n ratio and was only detected after the recovery with the Kitt Peak 4 m telescope in April 1984 and the availability of an accurate ephemeris.

3. OBSERVATIONS OF P/HALLEY IN 1986

The most critical period for astrometric observations of P/Halley is between perihelion passage on 9 February 1986 and the arrival of five spacecraft during the first half of March 1986. The elongation from the Sun will increase from ~ 8° on 9 February at perihelion to 47° on 9 March. The predicted, total magnitude remains constant around 4, and the declination decreases from ~ -10° to -20°. P/Halley will be observable from La Silla at a very low altitude above the Eastern horizon early in the morning. It will be seen against a comparatively bright sky and will, under the circumstances, be a relatively difficult object.

In view of the crucial importance of providing an accurate determination of the orbit of P/Halley, so that the ESA, USSR and Japanese spacecraft will be able to perform early mid-course corrections, a determined effort must be made to obtain very accurate, astrometric observations as soon as possible after perihelion passage. Rapid reduction and transmission of the obtained data to the spacecraft control centres must be ensured. However, P/Halley cannot be observed with telescopes in the northern hemisphere at this time and it is therefore the intention to carry out a special observing programme at La Silla in support of the Halley spacecraft missions. It is expected that the early observations will be made with the GPO, supplemented with Schmidt plates later in February 1986. On a few occasions, it may also be possible to obtain the highest possible astrometric accuracy by photographic observations with the 2.2 m and Danish 1.5 m telescopes with focal lengths of 17 m and 12 m, respectively.

The GPO can point towards the horizon and may be able to photograph P/Halley already around February 15-18. Very short exposures will be made through a red passband (probably 098-04 + RG 610) in order to improve the contrast between the cometary nucleus, the coma and the sky background. Only one exposure will be made per plate and two or three plates will be made each morning. The plates will be processed and measured (on a modified Zeiss blink comparator) as soon as they are dry. Certain technical improvements are being made on this machine which are expected to ensure that the positions can be measured with an r.m.s. of $\lesssim 1$ arcsec. Reductions will be made on the VAX 11/750 at La Silla and the data will be transmitted to JPL, as well as to the three spacecraft control centres by telex, telephone, Telenet or Decnet. It is believed that the time interval between the epoch of observations and the availability of the astrometric positions will be three hours or less.

REFERENCES

West, R.M., 1981, POS- and MP-Manuals, ESO

West, R.M., 1982, in Proceedings of ESO Workshop on Ground-based Observations of Halley's Comet, eds. P. Véron, M. Festou and K. Kjär, 263

West, R.M., Pedersen, H., 1983, Astron. & Astrophys., 121, L11-L12

D11

N85-25026

THE ASTROMETRY PROGRAMME AT MT. JOHN OBSERVATORY

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ABSTRACT

The observing methods and reduction procedures that are used in our comet astrometry programme are described and reviewed.

INSTRUMENTATION

The comet (and minor planet) astrometry programme uses one of two 0.6 metre (24 in.) Cassegrain telescopes at Mt. John University Observatory. The observatory is primarily operated by the Physics Department of the University of Canterbury, Christchurch, New Zealand. The observatory is 1000 metres above sea level on Mt. John, a hill rising 300 metres above Lake Tekapo, in the centre of the South Island of New Zealand.

For astrometric photographs of comets and minor planets a simple guide probe camera, made by the authors, is attached to the Cassegrain. Attached to it is an offsetting camera back that allows the plate to be moved to follow the predicted motion of the comet. It is shown in Figure 1. The camera back is rotated to the required position angle. During the exposure the plateholder is offset at the predicted angular speed. The offsetting is done manually via a micrometer. A toothed wheel on the micrometer engages a leaf spring. Incrementing by one tooth on the wheel moves the camera back by one second of arc in the Cassegrain focal plane. The method is essentially that described by Roemer (1962).

The camera uses 102 x 127 mm (4 x 5 in.) plates or film, giving a field of 40' x 50' at a scale of 24" mm^{-1}.

Astrographs

Frequently the Cassegrain field does not include sufficient catalogued stars for a satisfactory reduction. In these cases we then transfer the comet position to an astrograph plate. These plates are obtained with a variety of astrographs, all about one metre focal length. Exposures are usually 10 minutes on 103a-0 films or plates giving good images of stars in the magnitude range 8 to 12. There is also a 0.25 m f/7 astrograph that can be used with the offsetting camera. It gives a 3.3 x 4.4 degree field and is useful for locating objects of uncertain position down to magnitude 16.

Film

For economy we mostly use Kodak 103a-0 film on 0.2mm (0.007 in.) Estar base. The film is hypersensitised by baking for three hours at 65°C. then soaking in hydrogen at room temperature for a further 12 hours. The film is pressed against a clear glass plate to keep it flat during the exposure. In 2" seeing, measurable images can be recorded to B magnitude 19 in a 60 minute Cassegrain exposure.

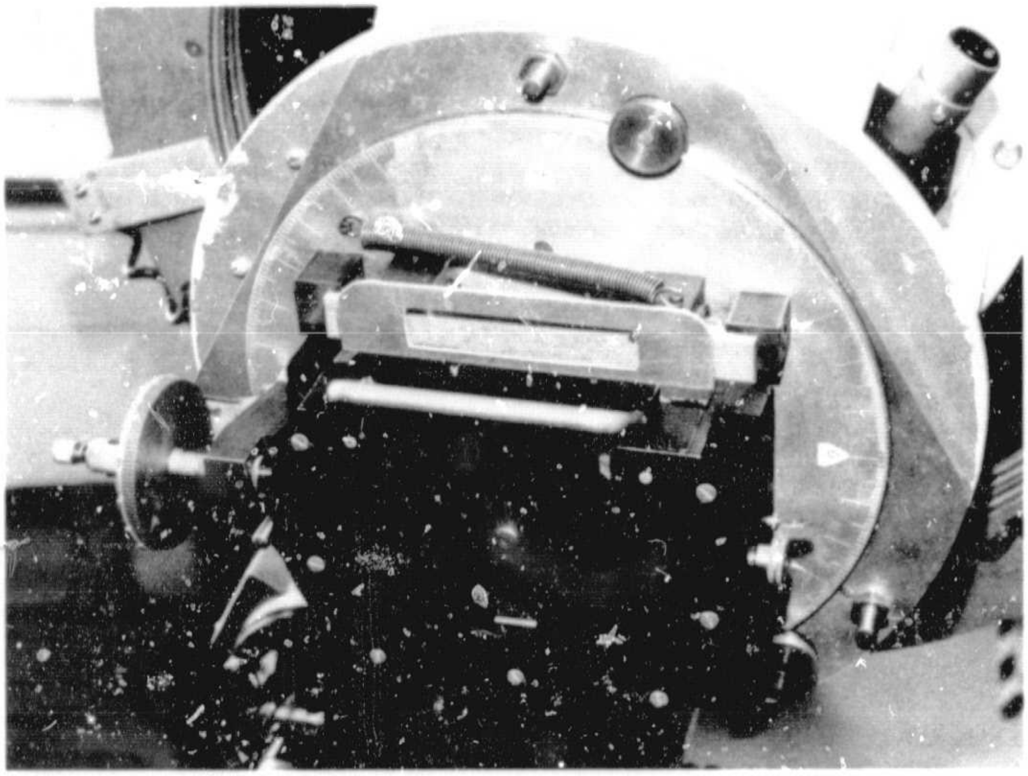

Fig. 1. The offsetting camera

OBSERVATION

Ephemerides

Ephemeris data is computed either on the Commodore microcomputer at Mt. John or on the author's Hewlett-Packard HP41C programmable calculator. Data is calculated to the tenth of a day nearest the meridian transit of the object or for dusk or dawn twilight for low objects. The ephemeris lists the 1950 and apparent coordinates of the object, the position angle of motion, the angular speed in seconds of arc per minute, the inverse speed in seconds of time per second of arc for offsetting, and the magnitude. The motion is simply calculated from the change of position over the previous day. For fast-moving objects, a shorter time interval is used.

Exposures

Exposures are made in pairs. This is essential if faint objects are to be distinguished from film flaws. The resulting pair of positions also providesa necessary check on the measurement and reduction.

Ideally, exposures are kept to the minimum length required to record a recognisable image of the comet. In practice, for slow-moving objects, the minimum exposure time is determined as much by the angular speed of the object as by its brightness. We find that the star trails need to be 0.3 mm long to make the moving object recognisable as a dot among trails. Unless the object is known to be bright we usually begin with exposures of 30 to 60 minutes.

The beginning and end of exposures are logged to the nearest second. The clock is checked against radio time signals each night. For each exposure we also log the sky conditions, seeing, and any other relevant information.

MEASUREMENT AND REDUCTION

Exposure Data

The exposure data are processed by a calculator program. The object's position, the beginning and end of the exposure, and the clock correction are entered. The program calculates the decimals of a day, the exposure length (as a check on the input data), and the mean air mass for magnitude estimates.

Catalogued Stars

We have the AGK3, SAO, Cape Photographic Catalogue (CPC), and the Perth 70 Catalogue. The AGK3 and the CPC are preferred for their density of stars and reliability of positions. In the declination interval -3° to -30° and -40° to -52° (the "Cape Gap") we use the SAO catalogue. The lower density of stars in the Perth 70 Catalogue makes it unsuitable for narrow-field instruments.

The small field of the Cassegrain can make the identification of catalogued stars difficult. To aid identification we use Atlas Stellarum (Vehrenberg 1970) along with Atlas Eclipticalis and Atlas Australis (Becvar 1958, 1964).

We like to have at least four catalogued stars on a Cassegrain plate. Up to eight are measured if available. For urgent astrometric positions we have used only three stars but in these cases a fourth star is measured and used as a check on both plates. In general if there are less than four catalogued stars then we transfer the measure to a field plate.

Field Plates

A field plate is used like the Astrographic Catalogue. Suitably exposed stars on both the Cassegrain and astrograph plates are identified. Further catalogued stars are identified around the region on the astrograph plate. The rectangular coordinates of the comet are transferred onto the astrograph plate and there reduced to equatorial coordinates.

Measurement

The measuring machine is a single-coordinate Gaertner kept at our house in Lake Tekapo village. Films are sandwiched between a pair of glass plates for measuring. The plates are simply oriented with the star trails in the x direction. Three settings are made on each end of the star trails, and six settings are made on the comet, in each coordinate. We measure the plate in one direction only.

Reduction

Because we orient the plateholder to follow the motion of the comet, and use this as the x-axis, there is no correspondence between the measured rectangular coordinates and standard coordinates. So we use the dependences method for reductions. The calculator program accepts rectangular and equatorial coordinates for eight stars and the rectangular coordinates of the comet. It then uses specified sets of three stars to derive the position of a specified fourth object. This keeps the number of keystrokes to a minimum. The computation method is exactly that given by Comrie (1929). Star measurement and identification are checked by reducing positions of catalogued stars. For these the program automatically displays the difference between the computed and entered position. If the internal accuracy checks are satisfactory then the comet position is reduced. Each reduced position is automatically assigned a weight and the program accumulates a weighted mean position. The transfer to, and reduction of, an astrograph plate is handled by a variation of the same program.

The pair of positions are checked by computing the speed and position angle of motion and comparing these with the predicted values. This check usually reveals any integral millimetre misreadings of the comet's position, the only error that is not checked by earlier calculations.

DEFICIENCES

Photography

The use of blue-sensitive emulsions is a disadvantage in a twilight sky. We have recently added a filter holder to the offsetting camera. We are planning to use red sensitive emulsion (notably Kodak 2415) behind yellow or red filters for exposures in bright twilight. This will be particularly useful for Comet Halley astrometry in February 1986.

A stepping motor with digital control on the offsetter would be helpful for fast-moving objects.

Measurement

That we measure our plates in one direction only flouts the tradition and may be regarded by some as a suspect method. We would argue that the subjective effects of measuring typical comets and star trails are small compared with the errors introduced by seeing, guiding and catalogue age. Also, because we take two exposures and check the motion computed from the pair of positions, we usually detect any of the gross errors that would otherwise be detected by a reverse measure. Since plate measuring is the slowest operation in the programme, doubling the time spent on it would cause a substantial loss of productivity with little increase in precision.

Reduction

A least-squares program that provided residuals for each catalogued star would be useful for astrograph plate reductions. The same approach could be applied to the Cassegrain films if they were measured at the same position angle as the original exposure. However, the subjective effects of setting obliquely to trail ends and the greatly increased chance of introducing orientation errors in measuring, make it unlikely that there would be a useful increase in accuracy or efficiency.

References

Becvar, A. 1958. *Atlas Eclipticalis*. (Prague, Czechoslovakia: Czechoslovak Academy of Sciences.)

Becvar, A. 1964. *Atlas Australis*. (Prague, Czechoslovakia: Czechoslovak Academy of Sciences.)

Comrie, L. J. 1929. Note on the Reduction of Photographic Plates. *Journal of the British Astronomical Association*. 39:203.

Roemer, E. 1963. Comets: Discovery, Orbits, Astrometric Observations. In *The Moon Meteorites and Comets*, ed. B. M. Middlehurst and G. P. Kuiper (Chicago: The University of Chicago Press), pp. 527-549.

Vehrenberg, H. 1970. *Atlas Stellarum*. (Dusseldorf, F. G. R.: Treugesell-Verlag KG.)

D12

N85-25027

THE ASTROMETRY NETWORK OF OBSERVERS IN CHINA

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ABSTRACT

In China, The Purple Mountain Observatory (32° 04'N and 118° 49'E), the Shanghai Observatory (31° 06' N and 121° 11'E) and the Qingdao Station (36° 05'N and 120° 19'E) will take part in the Astrometry of Halley's Comet. A brief account of the astrometric work together with the instrumentation used at these three observatories is given here.

1. The Purple Mountain Observatory

The Department of the Planet of the Purple Mountain Observatory will take part in the astrometry of Halley's Comet. The instrument is the Zeiss 40 cm Double Astrograph with a focus of 3M and a focal ratio of 7.5. Plates of 30 x 30 cm are employed to get a field of 5°.6 x 5°.6 with a scale of 68".5 per mm. In general, an exposure of one hour reaches 17th magnitude.

Since December 1949, the Purple Mountain Observatory has been engaged in the astrometric observations of asteroids and comets, first with the 15 cm astrograph, then the Zeiss 60 cm reflector and from the 1960's up until now with the 40 cm Double Astrograph. In the last 35 years, more than 8000 plates have been taken and more than 9000 accurate positions of asteroids and comets have been obtained. So far about 1000 unnumbered asteroids and 3 new comets have been discovered. Among them, 55 asteroids together with 3 comets have been officially confirmed and numbered serially by the International Minor Planet Center.

Six persons, including J. X. Zhang, J. X. Yang, the chief and deputy chief of the Department of the Planet, are to carry out the astrometric work on Halley's Comet. Most of them are veterans in the work of photographic astrometry of asteroids and comets for more than 10 up to 30 years.

To reduce the observed plates, the SAO catalogue is currently adopted and the method of six constants is used. According to a precision analysis of observations in the past years, the precision of our positions is about 1 sec of arc. For the fuzzy images of comets, the error might be a little larger.

As to the observations of comet Crommelin this Spring, difficulties were encountered due to the rainy weather, the faint fuzzy image and the comet's location near the horizon. The above mentioned persons of the Department, however, did not lose the relatively few hours of clear sky to get 18 positions for the "trial run" of this comet from February 7 to March 29. The results of the observations were sent to Dr. Yeomans at JPL and

Dr. Marsden at the Central Bureau of Astronomical Telegrams. Of these, six positions of the comet during March 22 to 29 (the official trial run dates and nearby days) were measured immediately, then computed and sent by Telex within 2 or 3 days.

2. The Shanghai Observatory

At Shanghai Observatory, the astrometry on Halley's Comet will be carried out by L. Wan, J. L. Zhao and L. S. Yan. The first two are, respectively, the chief and deputy chief of the Department of Photographic Astrometry and Stellar Astronomy. All three have worked in the field of stellar parallaxes and proper motions and/or astrometry of visual binaries more than 20 up to 30 years. A 40/690 cm astrograph, a Zeiss measuring engine and an AGK3 catalog are used for the astrometric work. For each observation, at least two plates will be taken so as to identify weak images. Ten reference stars are to be used in the reduction and the astrometric cometary positions will be referred to the mean equator and equinox of 1950.0.

In connection with the astrometric work, the Sheshan (Zô-Sè) Station of the Shanghai Observatory has, over a long period of time, made a fairly systematic study of the proper motions, spatial movement and dynamical evolution of the open clusters and the Orion stellar association. The proper motions of more than 100 RR Lyrae variables have been measured and a catalog of the proper motions of 168 RR Lyrae variables has been compiled.

Astrometric positions will be transmitted to the Orbit Determination Center by Telex, using the IAU Circular Code. This Observatory will also supply a pair of Giacobini-Zinner observations per week for the period August - September 1985. During the period of the Earth-Halley close approaches, a pair of observations will be supplied every 3 days (during October 1985 to January 1986).

3. The Qingdao Station

The Qingdao Station, formerly a part of the Purple Mountain Observatory, ceased to function in 1978. However it is going to be restored. Y. J. Shao of Beijing Observatory, S. S. Sun, a former staff member of Qingdao Station and X. Y. Ma of Beijing Planetarium will join together to conduct the work of astrometry on Halley's Comet. Shao and Sun have had more than 20 years of experience in the astrometry of stars, and planets and asteroids respectively. They will use the 32/350 cm astrograph of Qingdao Station. A badly needed Zeiss measuring machine will be borrowed from another institute. During the spacecraft encounters with the comets, comet position data will be sent rapidly by telegrams, or Telex, if possible.

DISCUSSION FOLLOWING PRESENTATION

B.G. Marsden: It is perhaps of interest to note that, during the official week for observations of P/Crommelin, we received more quickly telexed observations from Purple Mountain than from any other observatory in the world!

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N85-25028

THE ASTROMETRY NETWORK OF OBSERVERS IN JAPAN

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ABSTRACT

In this paper, the astrometric network of observers and the main telescopes for professional and amateur astronomers in Japan and their availability for the IHW are briefly described.

TELESCOPES

There are not so many astronomers in Japan who have been actively engaged in the astrometry of comets, except for many amateur cometary observers. However, when Halley's comet will appear, it is expected that many photographs of the comet which can be used for astrometry will be taken by using the telescopes listed in Table 1.

Table 1. Main telescopes for IHW astrometry

Station	Type	dia.	f	field	mag.	long.	lat.	h
Okayama	R	188cm	909cm	1°x 1°	20	133.°6	34.°6	372m
Kiso	S	105/150	330	6 x 6	21	137. 6	35. 8	1130
Dodaira	R	91	460	1 x0.8	19	139. 2	36. 0	879
Dodaira	S	50/65	100	5 x 5	18	139. 2	36. 0	879
Uchinoura	R	60	270	2 x1.5	18	131. 1	31. 2	270
Uchinoura	S	50/75	75	14 x 4	18	131. 1	31. 2	270
Geisei	R	60	240	2 x1.5	18	133. 8	33. 5	130
Tokai	R	30	150	1.5x 1	16	137. 4	35. 0	150

R: Reflector, S: Schmidt telescope, f:focal length, dia.:diameter, mag.:limiting magnitude, h:height

Among the listed stations Okayama, Kiso and Dodaira belong to the Tokyo Astronomical Observatory. However, facilities at Okayama and Kiso can be used not only by the staff of the Tokyo Astronomical Observatory but also by observers at other institutes. Observing programs at Okayama, Kiso and Dodaira are fixed once a year, once every three months and once a month, respectively, and it is expected that roughly 10 days, 20 days and 40 days, respectively, will be allocated to observe Halley's comet in the year of 1985. Observing time for the Schmidt at

Kiso will be shared with an asteroid survey. However, the Schmidt telescope at Dodaira can be used almost entirely for the IHW in the years of 1985 and 1986 if adequate observers are available. As the sky around the observing stations is not so dark, (except for Kiso) the limiting magnitudes in the table are estimated by taking into account the brightness of the sky. Kiso and Dodaira, as well as the main office at Mitaka of the Tokyo Astronomical Observatory, have x-y comparators and computing facilities.

Uchinoura is the rocket launching site of the Institute of Space and Astronautical Science and the Schmidt telescope there is used primarily for optical satellite trackings. However, as it has not been used recently, it is expected that it can be used entirely for the IHW.

AMATEUR GROUPS

There are several telescopes which can be and have been used by amateur astronomers in Japan. Of them two main telescopes are listed in Table 1. The telescope at Geisei is operated by T. Seki, one of the leading comet hunters, and Tokai is operated by a group of amateurs including T. Urata. They have their own x-y comparators.

Besides them, many amateurs are scattered around Japan, which is situated between 24° and 45.°5 in latitude and between 125° and 145.°5 in longitude. When the occultation of the star +10° 1142 by Halley's comet on January 7, 1984 was predicted about 10 people using telescopes at Sapporo of Hokkaido, Sendai in the north-east part of Honshu and so on, some with SIT cameras, tried to observe the phenomena, none of them being able to detect it.

Although there is no unified organization, there are several amateur groups in Japan. However, they meet together every year in October to present their research papers. Comet people, including orbit computing people such as S. Nakano, meet together there to exchange their information. In addition to the general annual meeting, comet hunters meet also in March. One of the main topics of this year's meeting was the IHW. It is expected that at the next meeting they will again discuss their observing networks for the IHW. Some of the Tokyo Astronomical Observatory staff will be involved in their networks as consultants.

D14 N85-25029

THE ASTROMETRY NETWORK OF OBSERVERS IN U.S.S.R.

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ABSTRACT

A list of observatories included in the Soviet Astrometry Network is given. Some aspects of Astrometry Network activity are discussed. A brief account on the Comet Halley star catalog is reported.

Among many important studies, the astrometric investigations are included in the Soviet ground-based observation program for comet Halley. A plan of coming works has been elaborated at the Workshop meeting "Position Observations of Comet Halley" held in Kiev in April 1982. At present, the following work has been done:

- the Network of stations for position observations of Comet Halley - the Astrometry Network- has been organized;
- basic principles of the Network activity have been formulated, and the instruction of observations has been compiled;
- some investigations in the field of cometary astrometry have been made and trial observations of comet Crommelin have been carried out.

The Astrometry Network includes 23 observatories and stations. The list of these observatories is given in Appendix. The position observations of comet Halley are expected to be made not only with astrograph and the Schmidt cameras, but also with the help of large telescopes; that is especially desirable for observations at great distances from the Sun. As the experience of such observations is scanty, trial cometary observations are carried on with reflectors and the astrometric properties of these instruments are studied at some observatories.

The activity of the Astrometry Network is regulated by special instruction, formulated in accordance with the navigation needs. The results of observations will be transmitted by TELEX, telegram or phone to the data center (Main Astronomical Observatory, Kiev) within one week but in the period September 1985 - March 1986 not later than within two days after observation. Then, these data will be immediately distributed to the Soviet and IHW orbit determination centers. In such a manner, the basic information - observatory, time of observation, right ascension and declination, observers, and measurer - should be transmitted. In addition, information concerning cometary images, circumstances of the observations and their reductions should be required. This information will be of use for current data analysis and will be sent monthly.

It has been decided to produce a special reference star catalog. The catalog should provide a sufficient number of stars for the data reduction of plates from long focus telescopes.The work is carried out at the Sternberg astronomical Institute. The catalog will consist of several parts. Each of the parts will contain a list of stars with their right ascensions and declinations, a set of star charts, and explanatory text.

Two parts of the catalog have been already completed. Part one includes 339 stars within one degree of comet Halley's path from September through December 1983. The star density is 45 stars per square degree with a magnitude range of $13-14^m$. The equinox is 1950.0 and the epoch is 1983.3. By intercomparison of coordinates from two determinations for each star, standard errors were derived to be $\pm 0^s.017$ and $\pm 0''.26$ in right ascension and declination, respectively. Part two contains 380 stars and covers the comet's path on the sky during January - May 1984. The star zone width and magnitude range are just the same as those in part one. The distribution of stars over the zone is not uniform. The density grows to the comet's ephemeris path, where it becomes approximately equal to 60 stars per square degree. The epoch is 1983.7. Standard errors are $\pm 0^s.013$ and $\pm 0''.17$ in right ascension and declination, respectively.

The reference stars are marked by pointers on the supplemental charts. The charts are made on the basis of the Palomar Atlas and reproduced at a scale 30"/mm. Coordinate lines are plotted in 2^m and 30' in right ascension and declination, respectively. Thus, the charts are used not only for identification of reference stars, but also for searching for the cometary image.

Both parts of the catalog produced in few copies, have been distributed to some observers. It is planned to produce 2-3 more parts for the period September 1984 through April 1985 and August - October 1985.

The necessary plates were taken with the Sternberg Institute wide-angle astrograph AFR-1 23/230 cm and 40 cm astrograph 40/160 cm. The plates taken with the astrograph AFR-1 serve for determination of the positions of some intermediate stars of $10-12^m$. The AGK3 stars serve as reference ones. The intermediate stars, in turn, are used for reduction of plates from 40 cm astrograph. The employment of such a two-step procedure was chosen for two reasons: firstly, due to the impossibility to use the objective grating on the 40 cm astrograph, and, secondly because the determination of plate constants obtained from the overexposed images of AGK3 stars might lead to large errors in the derived star positions.

In connection with conducting the space projects, the photographic observations of comet Halley and their reductions require due care.

Experience with position observations of comets and other bodies of the Solar system showed that one must keep the following rules:

i) Exposures should be just long enough to show the central condensation of coma and some reference stars. As to guiding, it has to be made after the manner of Metcalf.

ii) In order to eliminate the systematic errors of setting, the measurements of plates should be made in two positions, differing by 180°. It is also desirable that the setting should be made on each image in different positions of the reversing prism.

iii) A linear adjustment is sufficient in the case of a narrow field ($2^{\circ} \times 2^{\circ}$). More complicated reduction formulae, with 8 or 12 plate constants are suitable in the case of a large field. Measured coordinates must be corrected for differential refraction and a cubic distortion before a least-squares solution can be made.

Finally, we should like to say some words about the trial observations of the Comet Crommelin. On the whole, the experiment succeeded. The comet was observed at 13 observatories of the Soviet Astrometry Network. About 170 positions of the Comet Crommelin have been determined. A preliminary study shows that an r.m.s. error of one observation is of order 4".

We hope that the discussions held at this meeting will help to improve our work on cometary observations in the future.

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Appendix

List of Observatories engaged in the Soviet Astrometry Network

No	Observatory and its location	IAU Code	Telescope	D/F cm
1	2	3	4	5
1.	Engelhardt Observatory, Oktyabrsky (near Kazan)	136	Maksutov telescope 16" astrograph	35/120 40/378
2.	North-Caucasian Observational station of the Kazan University, Zelenchuk	114	Zeiss astrograph	40/200
3.	Kiev University Observatory, Kiev	085	Astrograph	20/430
4.	Kiev University. Cometary station, Lesniki (near Kiev)	585	Reflector AZT-8	70/1120
5.	Sternberg Astronomical Institute, Moscow	105	Astrograph AFR-1	23/230
6.	South Observational station of the Sternberg Astronomical Institute, the Crimea (near Nauchny)	095	Zeiss Astrograph	40/160
7.	Station of the Odessa Astronomical Observatory, Mayaki (near Odessa)		Astrograph Schmidt Camera	14/100 20/53
8.	Satellite station of the Uzhgorod University, Uzhgorod	061	SBG Camera	42/78

Appendix (continued)

1	2	3	4	5
9.	Sverdlovsk University Observatory, Novoutkinsk (near Sverdlovsk)	168	SBG Camera	42/78
10.	Main Astronomical Observatory, Academy of Sciences of USSR, Pulkovo	084	26" Reflector Astrograph Double Astrograph	65/1000 33/345 16/70
11.	Nikolaev Observatory, Academy of Sciences of USSR	089	Astrograph	12/204
12.	Institute of Astrophysics and Atmosphere Physics, Academy of Sciences of the Estonian SSR, Tartu	075	Astrograph	16/80
13.	Radio Astro-Physical Observatory, Academy of Sciences of the Latvian SSR, Baldone	069	Schmidt Telescope	80/240
14.	Zvenigorod station, Academy of Sciences of USSR	102	Zeiss Astrograph	40/200
15.	Main Astronomical Observatory, Academy of Sciences of the Ukrainian SSR, Kiev	083	Double Astrograph Double Zeiss Astrograph	40/550 40/200
16.	Crimean Astrophysical Observatory Academy of Sciences of USSR, Nauchny.	095	Double Zeiss Astrograph	40/160

Appendix (continued)

1	2	3	4	5
17.	Abastumani Astrophysical Observatory, Academy of Sciences of the Georgian SSR	119	Double Zeiss Astrograph	40/300
			Maksutov Telescope	70/210
18.	Byurakan Astrophysical Observatory, Academy of Sciences of the Armenian SSR	123	Schmidt Telescope	53/180
19.	Astronomical Institute, Academy of Sciences of the Uzbek SSR, Tashkent	192	Astrograph	33/345
20.	Kitab Latitude station of the Astronomical Institute, Academy of Sciences of the Uzbek SSR	186	Double Zeiss Astrograph	40/300
21.	Gissar Astronomical Observatory of the Institute of Astrophysics, Academy of Sciences of the Tadjik SSR	190	Zeiss Astrograph	40/200
22.	Astrophysical Institute, Academy of Sciences of the Kazakh SSR, Alma-Ata	210	Maksutov Telescope	50/113
23.	Coronal station of the Astrophysical Institute, Academy of Sciences of the Kazakh SSR, near Alma-Ata.		Schmidt Telescope	40/80

DISCUSSION FOLLOWING PRESENTATIONS

At the conclusion of this sesson, a general discussion of observing techniques took place and the following comments have been recorded.

P. Wild: How important is the use of a red filter for the accuracy of positional measurements?

R.M. West: A red filter enhances the contrast between the nuclear region and the surrounding coma.

L.G. Bowell: It can also be important for cutting down the effects of refractive dispersion.

B.G. Marsden: On the other hand, it is not apparent from orbital analyses that positions obtained with the use of a red filter are any better than those that are not.

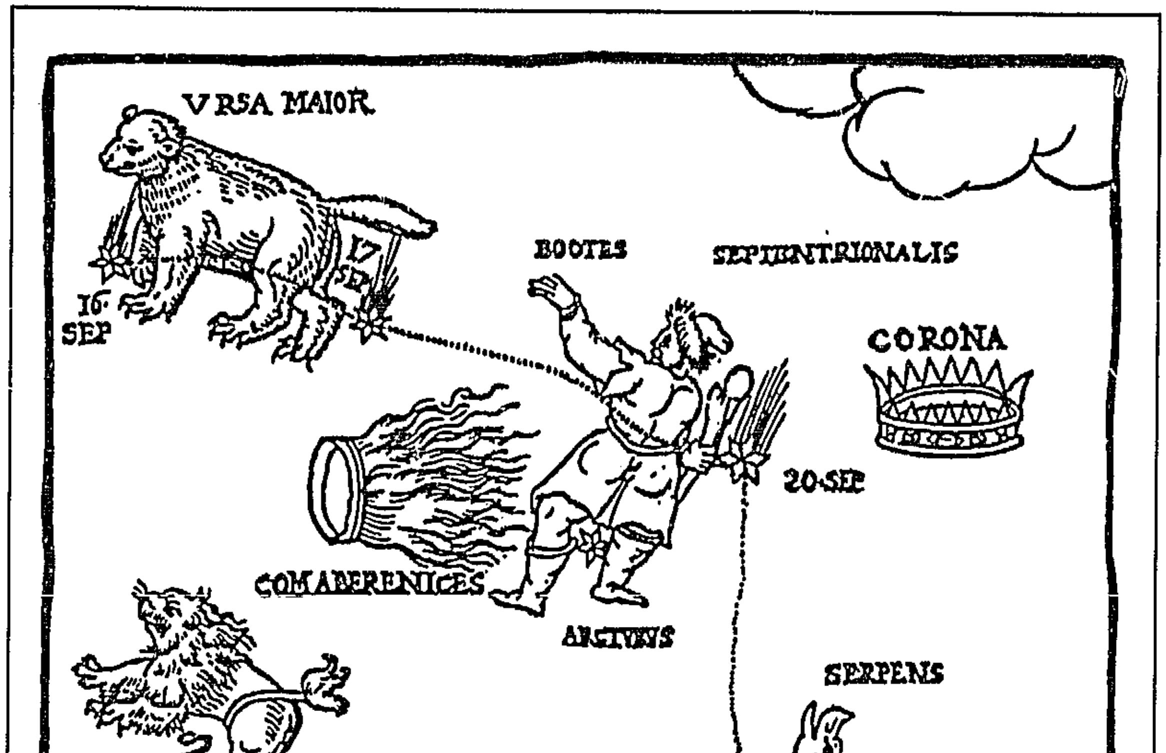
J. Gibson: It is likely that visual to red filters and plates may give a better penetration of the coma to detect the nucleus than will blue-sensitive plates, but we don't know how such a comet as P/Halley behaves in the red. Should we advise some observers to have both blue and red sensitive plates available with a variety of filters and experiment to find the most effective combinations as the comet brightens? If we could see spectra of the comet in the red as well as the blue as it brightens, we might make better choices. The dispersion need not be high; spectral classification dispersion would be adequate, but the the spectra should be from a grating slit spectrograph, not from objective prisms or prism spectrographs. They should be unwidened, exposed so that the spectrum of the nucleus is clearly visible. Then we might either select wavelength ranges to avoid the major emission features of the coma or take sufficiently broad passbands so that the effect of one or two moderately strong emission features will be diluted. But whether any filter and emulsion combination will make it possible to detect the nucleus through a dust coma remains a subject for experimentation or for world-wide observations in the hope that some observer will be looking when the dust coma may thin temporarily as the comet is near perihelion, approaching or departing.

P. Wild: In the case of a faint comet with a not very pronounced central condensation, guiding at sidereal rate usually gives a more regular picture than trying to guide on the comet. But it seems to me that an asymmetry is introduced because the beginning of the faint trail needs some time to get above the threshold intensity. One is tempted to allow for the effect in the reported time of the exposure.

J. Gibson: I would like to mention an observing technique used occasionally on the Palomar 48 in. Schmidt for brighter comets and minor planets. As in Wolf's technique for asteroid searches, the telescope is guided at sidereal rate. The exposure is either the shortest possible (10 seconds) for the fastest moving objects, or the time in which the object will move by two diameters of a faint star image, say 3 to 4 seconds. The resulting short trails can be measured with only a slight loss of accuracy, compared to perfectly round images. At my suggestion and request, A. Saha took 10 second exposures of comet IRAS-Araki-Alcock (1983d) on two nights near its closest approach to the earth. These observations yielded satisfactory positions. If a comet nucleus is bright enough to produce a trail on the plate, that trail may be less affected by the coma of the comet than an equally long exposure guided at the rate of the comet. A trailed image may show detail which is overlain by the growth of the image in an exposure guided to produce a round image of the object. Two trailed images of the minor planet 1983 TB, taken shortly after discovery, seem slightly "softer" on the sunward side of the trail than on the opposite side. This may be evidence that this short period object, with a comet-like orbit, may still be active near perihelion. Equally long exposures at the rate of motion of the planet produced a larger image with no trace of structure.

Though this technique may not be useful to observers with small or slow telescopes, it is possible that the nucleus of P/Halley may be bright enough to register on sidereal rate exposures with telescopes of modest size - say 0.4 or 0.5 meter apertures and 2 meter or greater focal lengths. Such observers should not withdraw from the Halley Watch without trying this technique as the comet brightens.

Star Catalogs



Adapted from a woodcut illustration from a 1607 German broadside showing a recently discovered comet (Halley) moving through the constellations.

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DESIRED CHARACTERISTICS OF CATALOGS FOR COMETARY ASTROMETRY

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ABSTRACT

Reference star catalogs for cometary astrometry have to provide an all-sky coverage with suitable stellar density and limiting magnitude on a fundamental coordinate system. A general catalog meeting all these requirements will not be available for a foreseen timescale. The suitability of various existing catalogs for cometary astrometry is discussed.

1. INTRODUCTION

Reference star catalogs suitable for cometary astrometry have to overcome some special problems which only arise with this type of object .

(1) Comets are moving objects against a fixed stellar background, the path of a single comet may describe a very large arc on the sky.

(2) The appearance of cometary images will be highly variable extending from pointlike structure to several degrees diameter.

(3) The brightness of images may cover the whole range of magnitudes.

(4) The reference frame for cometary astrometry shall be an inertial frame which allows an unambiguous interpretation of cometary kinematics and dynamics.

Conditions (2) and (3) impose heavy restrictions on those catalogs, the ideal realization would call for an "all-sky catalog" with a very high surface density and large magnitude range of the reference stars.

Depending on the particular appearance of a comet, very different types of telescopes will be used with typical requirements for the reference star catalogs:

a) Full field reduction of astrograph - or Schmidt plates
about 6° x 6° field size, about 1*/sq. dg. ≙36* , magnitudes about 8-9

b) Full field reduction of typical RC-primefocus plates
about 3o' - 6o' field size, about 3o*/sq. dg. ≙ 2o* - 3o*, magnitudes about 14

c) Reduction of CCD-camera frames
about 2' x 2' field size, about 1*/arcmin^2 ≙ 36oo*/sq. dg. magnitudes very faint, ≥ 18

The above quoted conditions, which should be fulfilled for a satisfactory plate reduction, clearly show the difficulties if an existing catalog shall be used for this work. Indeed, no catalog exists with more than 1o*/sq. dg., and no catalog extends beyond 1oth magnitude. Furthermore, there is no catalog with the required positional accuracy covering the whole sky.

It is therefore unavoidable either to combine different catalogs in each particular area of the sky or to construct a special catalog for a particular comet as it is done in the case of comet Halley.

2. SURVEY OF CATALOGS

Although a large number of positional catalogs are available now from transit circle (TC) observations and photographic astrometry only a small fraction is applicable directly to modern high accuracy cometary astrometry. The following catalogs probably will provide the best compromise with respect to the desired characteristics of an ideal catalog discussed in the introduction.

a) The International Reference Star System (IRS)
The global primary reference star system for all kinds of large field photographic astrometry will be the IRS which contains about 4o,ooo stars and is mainly a combination of the AGK3R (Northern hemisphere) and the SRS (Southern hemisphere) catalogs. These catalogs include the stars with the best observational history to provide both positions and proper motions of highest accuracy for application within a large range of epochs. However, the IRS is not available as a global catalog, therefore the discussion has to be split up according to both hemispheres. The IRS provides a stellar density of about 1*/sq. dg., stars have been selected mainly from the visual magnitude interval 7-9. (For a detailed discussion see Smith, 198o, and Eichhorn, 1974, for general information).

Northern Hemisphere
The AGK3R contains 21499 stars between declinations +9o° and -5° with an average positional accuracy of o".1 at mean epoch 1958 on the FK4 system. To extrapolate these positions to other epochs, a proper motion system has been constructed at USNO by Th. Corbin (1974, 1979) with an average accuracy of ±o".oo45/yr. This updated catalog version AGK3RN contains all relevant information to compute positions at any epoch. The positional accuracy at 1984 is about o".2.

Southern Hemisphere
The southern hemisphere is covered by the SRS (Southern Reference Stars) catalog containing 2o495 stars between declination -9o° to +5°, therefore providing an overlapping zone with the AGK3RN. The SRS will be available probably at the end of 1984. The positional accuracy is about ±o".1 at mean epoch 1966. At present no p.m. system is available but work at USNO has been started. The expected accuracy of the p.m. will be in the range ±o".oo5/yr to ±o".oo8/yr (Smith 1984). As an intermediate catalog the

WL 50, which forms a basic part of the SRS, should be used. Due to the history of astrometric observations, it is obvious that the southern hemisphere is handicapped which causes an unavoidable discontinuity at the celestial equator.

The IRS is the optimal system for the reduction of large fields (astrograph, Schmidt camera) and great efforts are made to preserve and improve the quality of this primary global catalog system. At USNO reobservations of the SRS have been started with the 7-inch TC at New Zealand, and the AGK3R will be reobserved from Washington with the 6-inch TC. In contrast to this extensive observing program, the HIPPARCOS Astrometry Satellite wil' measure only a fraction (about 30,000) of the IRS stars.

b) Secondary Catalogs

To obtain sufficient reference stars for the reduction of smaller fields, and to extend the primary system to fainter magnitudes, various photographic positional catalogs have been constructed which provide a stellar density of about 10*/sq.dg. and a magnitude range between 7-10.

Northern Hemisphere

The AGK3 catalog (Heckmann et al. 1975), containing 180,000 stars up to the 10th photographic magnitude in the declination range +90° to -2°, is the optimal catalog for cometary astrometry on the northern hemisphere. It contains positions and p.m. which allow an extrapolation of the original catalog epoch (about 1960) to any desired epoch. The positional accuracy at epoch 1984 is about ±0".4. The AGK3 is on the FK4 system; for very critical applications, possible small systematic deviations between the AGK3RN and AGK3-system at epochs $\neq$ 1960 should be considered.

Southern Hemisphere

On the southern hemisphere no complete catalog similar to the AGK3 is available at present. Great efforts are being made to finish the reductions of the Cape Astrometric Survey (CPC2) which covers the whole southern hemisphere with a fourfold plate overlap. (See for example Nicholson, 1979, Nicholson et al. 1984).

At present reductions of the Cape zone (-40° to -52°) of this catalog have been finished. This catalog contains 51018 stars up to the 10th visual magnitude with a positional accuracy of 0".1 at mean epoch 1962 and improved p.m. for 22731 SAO stars in this zone have been provided. A tape version is available from CDS-Strasbourg. According to this unsatisfactory situation, the use of the SAO catalog is the only alternative. However, the present positional accuracy is > 0".5 and large systematic errors up to 1"-2" have to be expected, especially in the polar zone.

Again it is obvious that the southern hemisphere needs great astrometric efforts to provide a satisfactory reference frame of fainter stars.

c) Positions of fainter stars

If positions of fainter stars are required for the reduction of RC-telescope plates or even CCD-frames, special plates have to be taken with astrographs to provide intermediate secondary reference stars. For the reduction of those plates, again the AGK3RN or the SRS are recommended. This approach works adequately if the comet-plates have about the same epoch as the astrograph plates. To obtain positions of faint stars at any epoch the situation will be very complicated because p.ms have to be provided for faint stars. In principle this can be achieved using the different zones of the Astrographic Catalog or special other zone-catalogs. However this requires sophisticated new reductions of the old catalog data. As an example of this approach, the new reduction of the orbit of comet Schorr 1918III could be consulted (de Vegt et al. 1982).

A general solution of this problem can be obtained from a final new reduction of the Astrographic Catalog which is under consideration now.

3. REMARKS ON CATALOG SYSTEMS

In each of the quoted catalogs, systematic errors have to be expected. Those errors may depend on position, magnitude and spectral type. Of special interest in this context are the local representation of the catalog reference frame in the (small) plate field containing the comet's image and the global deviation of the catalog system from the inertial reference frame. For the IRS, local deviations should be < o".1, for the AGK3, slightly larger figures have to be expected, whereas the SAO could reach > o".5 in particular areas. Furthermore, one has to bear in mind that, mainly due to the influence of systematic errors of the p.m., all catalogs continuously deviate from their initial system at the epoch of catalog construction. For example the AGK3, which is based on the AGK3R-reference frame at epoch 196o, could be off by about o".o5 in 1984 if we would assume a systematic p.m. error of o".oo2/yr. Therefore only continuous reobservation at suitable intervals will preserve a homogeneous systematic catalog accuracy.

Relation to an Inertial Reference Frame

With view to all studies of cometary kinematics and dynamics, the observations should be made in an inertial reference frame. Whereas in the radio domain encouraging progress in the construction of an extragalactic reference frame has been made, investigations of the relation of this radio reference frame to the present optical FK4-reference frame are at the very beginning. A first comparison of the radio reference frame with the AGK3RN catalog, based on optical and radio positions of about 3o quasars and 2o radio stars has brought evidence that large scale systematic differences with local amplitudes up to o".15 between both systems might be present (de Vegt and Gehlich, 1982, Florkowski et al., 1984).

An additional problem will arise with the change of the present B 195o.o catalog system to the new IAU-1976 system J 2ooo.o . Whereas for radio position catalogs this transformation is relatively simple, the conversion of existing optical catalogs provides more difficulties due to the principles of their construction.

4. FUTURE CATALOG WORK

There are several projects which could improve considerably the present catalog situation. The HIPPARCOS Astrometry Satellite, to be launched in early 1988, shall observe 1oo,ooo stars at mean epoch 199o with accuracies of ±o".oo2 for positions and ±o".oo2/yr for proper motions. This space mission will then provide for the first time a global reference star catalog with an average density of 2.5*/sq.dg., containing mainly stars ≤ 9 B-magnitude. Within ±1 decade from 199o the accuracy of this system is better than o".o3.

As an experiment added to the HIPPARCOS mission, the TYCHO-project will provide positions of additional 4oo,ooo fainter stars ≤ 1oth magnitude with an accuracy of ±o".o3 at epoch but no p.m. system (Hög, 1982).

New groundbased catalog projects, extending the present magnitude limits of ≤ 1o to about 14, would be of greatest importance. In connection with the USNO-New Zealand project, the twin astrograph will be used to photograph the southern and later the northern hemisphere. Furthermore, a feasibility study of an AGK4 project has been made (de Vegt, 1979), which could provide a positional accuracy of about o".o6 with a limiting visual magnitude of 14 and will then be based on the HIPPARCOS reference frame. In this context, the construction of a very precise proper motion system for all stars down to 14th magnitude is of greatest importance. As has been discussed already frequently in the last years, this system could be obtained from a final new reduction of all zones of the Astrographic Catalog and, for the northern hemisphere, from a remeasurement of the AGK2 plates. Expected accuracies of the p.m. would be ±o".oo15/yr to o".oo3/yr, which then would allow an extrapolation of the new catalogs over several decades without degrading substantially their initial positional accuracy.

Finally, the Space Telescope Guide Star Catalog will contain about 2o million stars between magnitudes 9 and 14.5 with a positional accuracy of about o".5 (Jenkner, 1984) and will provide then an excellent data base for fainter stars.

5. CONCLUDING REMARKS

In the previous sections the present catalog situation has been summarized and forthcoming catalog projects have been discussed. Concerning the problem of a satisfactory reference frame for high accuracy cometary astrometry, we are left with some unfavourable facts:

1) There is no all-sky catalog available containing sufficient stars > 1oth magnitude.

2) The best existing catalogs (IRS) may deviate from an inertial radio reference frame by ≈ 0ʺ1.

3) Even with results from space astrometry (HIPPARCOS, ST) the problem of a global reference star catalog for fainter stars > 10th magnitude is still unsolved.

4) High accuracy cometary astrometry is only possible by construction of special catalogs, optimized for each particular object.

REFERENCES

Corbin,Th.: 1974, Thesis, University of Virginia
Corbin,Th.: 1979, Proc. IAU Coll. 48 Wien 1978, p.505
de Vegt,Chr.: 1979, Proc. IAU Coll. 48, Wien 1978, p.527
de Vegt,Chr., Gehlich,U.K.: 1982, Astron.Astrophys. 113, 213
de Vegt,Chr., Kohoutek,L., Marsden,B.G.: 1982, Astron. Astrophys. 114, 147
Eichhorn,M.: 1974, Astronomy of Star Positions, F. Ungar Publ. N.Y.
Florkowski,D.R., Johnston,K.J., de Vegt,Chr., Wade,C.M.: 1984, Proc. IAU Symp. 109, Astrometric Techniques, in press
Heckmann,O., Dieckvoss,W., Kox,H., Günther,A., Brosterhus,E.: 1975, AGK3 Star Catalog, Hamburg
Hög,E.: 1982, Proc. HIPPARCOS-Coll. Strasbourg 1982, ESA SP177, 21
Jenkner,H.: 1984, ST-Newsletter 1, No.2, 12
Nicholson,W.: 1979, Proc. IAU Coll. 48, Wien 1978, p.515
Nicholson,W., Penston,M.J., Murray,C.A., de Vegt,Chr.: 1984, MNRAS 208, 911
Smith,C.: 1980, Mitt. Astron. Ges. 48, 95
Smith,C.: 1984, private communication

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THE IHW REFERENCE STAR CATALOGS FOR COMETS HALLEY AND GIACOBINI-ZINNER

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ABSTRACT

After catalogs in general are discussed, the specific catalogs that should be used for these two comets are described.

CATALOGS

Before describing the IHW reference catalogs, I want to discuss catalogs in general and the various types that are available. The general catagories of catalogs are observed and compiled. Observed catalogs are tabulations of positions determined with a single instrument (transit circle or astrograph) at a single location with a single approximate mean epoch. Compiled catalogs are produced from a combination of observed catalogs and have the advantage of many more observations per star. They may also have proper motions, making them useable at future epochs.

In addition, catalogs may be classified according to their density and type of instrument used to produce them. A type 1 catalog is a truly fundamental catalog, produced by transit circles, and put on an established coordinate system in a fundamental way. It contains stars brighter than about sixth magnitude at a density of 1/20th of a star per square degree. The classic compiled catalog of this type is the FK4, which defines the current system of all astrometric catalogs. Coming soon will be the much improved FK5, with new constants and new theories, and based on the equator and equinox of J2000.

A type 2 catalog is also based on transit circle observations, but the system is established differentially with respect to a type 1 catalog. These go down to around the 9th magnitude, and they have a density of about 1 star per square degree. At present the major effort underway on a catalog of this type is the work on the IRS (International Reference System), which is composed of the already completed AGK3R' in the North and the SRS in the South.

A type 3 catalog is obtained photographically with astrographic instruments, and its positions are obtained differentially with respect to a type 2 catalog. They also go down to somewhat fainter than 9th magnitude, but their densities are usually of the order of 10 stars per square degree. A good, modern type 3 catalog exists for the northern hemisphere, and it is known as the AGK3. There is at present no really good catalog of this type for the southern hemisphere.

A compiled catalog which is a combination of all of the above types is the familiar SAO catalog, generated initially to provide reference stars for artifical satellite tracking, among other things. There is now a much improved version of this, known as the SAO (ADC 1984), which is supposed to have all of the major errors and blunders of the SAO removed. This is now available from the various stellar data centers.

A type 4 catalog is designed to give the density required for use with long focus instruments, and it is obtained photographically - differentially with respect to a type 2 or type 3 catalog. These go down to at least 12th magnitude, and the density is around 50 stars per square degree. The only catalog of this nature presently available for the entire sky is the old Astrographic Catalog, but there are programs under way in Russia, Germany, and the US to observe modern versions of this type of catalog.

THE COMET CATALOGS

As for the IHW Halley catalog, this obviously has to be a combination of various types, based on the part of the orbit being covered and the expected magnitude along that sector. The part of the catalog covering the sector from the beginning of 1984 until August of 1985 has to be a type 4 catalog, since the comet will be too faint to be observed by anything except long-focus, large aperture telescopes. There have been two efforts to obtain such a catalog, one by the Moscow group that has been mentioned previously, and one by Klemola, Jones, Franic, Harlan, and Nakajima at Lick Observatory. The Lick list is complete, and it contains positions and rough magnitudes for 5148 stars of visual magnitude mainly 13 and 14. It has been reduced to the AGK3R by an iterative overlap procedure, and its approximate mean epoch is mid-1983. The Moscow group has published only the first part of their list , and it has no overlap with the Lick list. Hence, the present catalog has merely copied these two lists, but the final one will combine the data in some judicious manner.

A year or so after the Fall of 1984 the comet will be bright enough to be observed with short-focus astrographic type instruments, which means a type 3 catalog is required. For the northern hemisphere, the AGK3 is the obvious choice. Actually, AGK3 stars along the entire northern hemisphere path down to -2° are included, in case anyone wants to do his own cascading during the fainter period. The southern hemisphere is more of a problem, since the best thing available is the SAO (ADC 1984), which has serious systematic problems in the South. Hopefully something better will come out of the various efforts in the South, and in any case it seems likely that southern hemisphere measures will have to be rereduced at a later date.

One segment of the orbit in which the absolutely highest possible accuracy is required is the segment covered from post-perihelion recovery to final pre-rendezvous orbit update. This, unfortunately, is in the South, running from approximately -12 degrees to -22 degrees. To cover this region, a small type 2 catalog is being constructed by the U. S. Naval Observatory, using the 15-cm transit circle in Washington, DC, and the 20-cm transit circle in Flagstaff, AZ. This will involve around 400 stars, to be observed this summer (1984) and possibly next. Proper motions will be available for these stars, but these will hardly be necessary. The reduction of these data will determine the date of issue for the final catalog, but it will be in plenty of time for distribution to the network, and the preliminary version is adequate through December 29, 1985.

Finally, there is the Giacobini-Zinner catalog. This comet is going to be most cooperative, in that it will be nicely placed in the northern hemisphere from recovery to well past "I.C.E." rendezvous. Hence, the IHW catalog will be the relevant data copied from the AGK3. Unfortunately, there is no effort underway that I am aware of to produce a type 4 catalog, although one would be most useful f a good portion of this apparition. At no point will the comet be bright enough to require a type 2 catalog. SAO stars are included for Southern declinations so that the catalog covers the comet's path through December 1985.

Both the preliminary Halley catalog and the Giacobini-Zinner catalog are now available from either the Eastern or Western network coordinator or from the Naval Observatory. The Halley catalog contains 16,163 stars (3618 from AGK3, 5148 from Lick, 7058 from SAO, and 339 from Moscow), making it much too big to be widely distributed in anything other than machine readable form. The G-Z catalog has 12,098 stars, and it usually will come as the second file on the Halley tape. Things like density, blocking-factor, character code, etc. should be specified as part of any individual request. Special cases can be dealt with as they arise, but it is expected that the present format will take care of most cases in the next three years.

D/7

N85-25032

OBTAINING ACCURATE COMET POSITIONS DESPITE SOME INACCURATE CATALOG STARS

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ABSTRACT

From an astrographic negative a grid is determined from measurement of all the reference stars and using their catalog positions, and other grids from selections of reference stars. These grids are determined from many stars, and individual stars will have errors with respect to the grid. Then there are three ways to identify stars "X" that are not at their cataloged position: (1) Determine the focal length of the telescope from the measurements of each pair of stars and look for discordant results, (2) Stars "X" are several arcseconds off the grid, and the other stars fit better when stars "X" do not help determine the grid, (3) The grid is stretched or distorted to include the stars "X". It is the author's impression that 15-20% of the stars in the S.A.O. catalog are 1.5" or more off their catalog positions. An interactive session with a computer can find and eliminate these errant stars and result in more accurate comet positions.

FOCAL LENGTH OF TELESCOPE FROM PAIRS OF STARS

Of course the first error check is to measure the negative both before and after a 180° rotation and insist that the sum of the two x-measures for each star add nearly to the same number. The y-measures get the same test. This will correct errors in transcribing the measuring engine readings. The next step is to determine the focal length of the telescope from each pair of reference stars. Let Θ be the computed angle in radians between a pair of stars from their catalog positions. This is equated to s/F, where s is the distance between the stars as measured on the negative, and F is the focal length of the telescope. See Table I.

Table I. Focal length of telescope determined from each pair of reference stars. Comet Taylor 1983u, 1983 Dec 2.36458.

Star pair,	then Focal Length(mm)						
2 - 1	2219	5 - 2	2223	6 - 5	2222	8 - 1	2229
3 - 1	2458	5 - 3	2189	7 - 1	2223	8 - 2	2228
3 - 2	2480	5 - 4	2220	7 - 2	2223	8 - 3	2313
4 - 1	2225	6 - 1	2224	7 - 3	2293	8 - 4	2227
4 - 2	2226	6 - 2	2224	7 - 4	2221	8 - 5	2226
4 - 3	2291	6 - 3	2254	7 - 5	2222	8 - 6	2227
5 - 1	2223	6 - 4	2221	7 - 6	2222	8 - 7	2228

It is evident from this table that star #3, which was SAO 96709, in a pair with any other star gives the wrong focal length. Either star 3 had its coordinates transcribed incorrectly, or it was mis-identified on the measuring engine, or the catalog is grossly in error. We checked the first of these, so the error was one of the latter two possibilities. In any case star #3 was discarded.

STARS THAT DO NOT FIT THE GRID

Table II is the result of measuring a negative taken of Comet Černis. Columns A and B are from the direct measurements, and C and D are from measurements after the negative was rotated 180°. The notation (12345) means that the plate constants were determined using all 5 stars, and (1345) means that they were determined by stars 1, 3, 4, and 5. It is clear that the fit is better without star 2, and that its position is off nearly 4" from a value consistent with the other stars. Star 2 is SAO 147847. Its catalog position was copied correctly and is quite probable that its catalog position really is 4" off. The comet's position reported was 1h 29m 58.52s, -14° 35' 45.1". With star 2 included as a reference the last digits would have been 58.53s and 44.7". It must be admitted that the improvement is often marginal. Looking at these errors for each star has sometimes caught errors that were missed in other checks.

Table II. Fit of 5 reference stars to the grid, Comet Černis negative taken 1983 Oct 1.26076.

Star number, then error in position from grid.

A	(12345) direct	B	(1345)	C	(12345) reverse	D	(1345)
1	0.93"	1	0.02"	1	0.95"	1	0.05"
2	1.88"	2	3.93"	2	1.91"	2	3.99"
3	1.02"	3	0.30"	3	0.51"	3	0.79"
4	1.38"	4	0.27"	4	1.88"	4	0.69"
5	0.46"	5	0.05"	5	0.57"	5	0.14"

In some cases it is not possible to know which star to eliminate. For example, stars 7 and 8 may have positions inconsistent with each other by 3". Making the grid using #7 shows a good fit to #7 and all the other stars, but a bad fit to #8. However, using #8 instead shows a good fit to #8 and the other stars, but a bad fit to #7. This can happen if stars #7 and #8 are close to each other, but rather far from the other stars. One must decide whether to use both or neither.

Sometimes there is a way to tell whether a bad fit to a reference star is probably real, or whether it is experimental error on the measuring engine. The direct and reverse measures, before and after the negative was rotated 180°, are independent. Thus a star must fit poorly on both measures before one can conclude that the stars's catalog position is wrong.

THE STRETCH FACTOR

The solution for the plate constants by the usual method, as in Smart, 1980, determines 6 constants in a least square sense from the positions of all the reference stars. Thus the standard coordinate in the direction along the line of right ascension is Ax + By + C, and that along lines of declination is Dx + Ey + F. Here x and y are perpendicular measurements on the negative, and they may be in any orientation with respect to the sky. The ratio of the plate stretch in right ascension to the stretch in declination is

$$\text{stretch factor} = \frac{(A^2 + B^2)^{\frac{1}{2}}}{(D^2 + E^2)^{\frac{1}{2}}} \tag{1}$$

In some cases looking at the stretch factor may help one decide which stars to reject and which to keep. A stretch factor very different from unity may mean the plate or film has really stretched. More likely, it means that the plate constants are trying to accomodate a star whose catalog position is inconsistent with its measured position on the negative, particularly if the stretch factor for that plate or film is ordinarily near unity.

An example of this: For Comet Austin, 1983 Feb 7.22951, there were 9 reference stars, of which #2 and #8 were definitely bad fits, and either #1 or #3 should be discarded. The stretch factor made the decision. Leaving out 1, 2, and 8 the stretch factor was 1.0195, whereas leaving out 3, 2, and 8 the stretch factor was 0.9999. Clearly the latter choice is indicated. This made a difference of 0.02s and 0.3" in the reported position.

Another situation where the stretch factor may be useful would be where there are only 4 reference stars, but where the stretch factor was rather far from unity when all 4 were used. Assume this is because one star is wrong, but which one? There are four ways to use four stars, 3 at a time. If three of these ways shows a stretch factor not close to unity, and one way has it close to unity, this last way contains the three good stars.

Every observatory has a program for obtaining comet and minor planet positions from reference star positions and measuring engine readings. If they all included the simple checks described here, then there ought to be a considerable improvement in accuracy.

REFERENCE

Smart, W. M. 1980. Textbook on Spherical Astronomy. (Cambridge, England, Cambridge University Press). Revised by R. M. Green, 6th Edition, Reprinted. See Ch XII.

D18

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REDUCTION OF ASTROGRAPHIC CATALOGUES

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ABSTRACT

An automatic program for the reduction of overlapping plates is described.

INTRODUCTION

A wealth of almost untouched astrometric information has been accumulated from the beginning of this century on the Carte du Ciel plates. Most of this material is available only in the form of rectangular coordinates for each plate. For some zones the plate constants needed for a transformation to equatorial coordinates are given. These, however, were not derived with plate overlap constraints. The latter is also true for a number of more modern and fully reduced astrographic catalogues. Last, but not least, even the catalogues which give equatorial coordinates are not on a uniform system. Not only do their equinoxes differ, they are also based on different fundamental systems. A recovery of all astrometric information and a reduction on a uniform system form an enormous task. It is worth the effort, though, particularly in view of the HIPPARCOS project and the possibility of an extragalactic reference system, to develop procedures which make such a task feasible. Here we present the test on such a procedure.

THE PROJECTION AND TRANSFORMATION EQUATIONS

As was shown by one of the authors (Stock, 1981), it is practical to convert the plate coordinates into three-dimensional coordinates on a unit sphere, when one wishes to impose plate overlap constraints. The following equations are used:

i) The Right Ascension α and Declination δ of a catalogue star are transformed into the three-dimensional coordinates ξ_1, ξ_2, and ξ_3, by

$$\xi_1 = \sin\alpha \cos\delta \tag{1}$$

$$\xi_2 = \cos\alpha \cos\delta \tag{2}$$

$$\xi_3 = \sin\delta \tag{3}$$

ii) The plate coordinates X, Y are transformed into three-dimensional coordinates u_1, u_2, and u_3, with F being the scale factor, by

tangential projection

$$\tan r = (X^2 + Y^2)^{1/2}/\ F \tag{4a}$$

$$u_1 = (X \cos r)/\ F \tag{5a}$$

$$u_2 = (Y \cos r)/\ F \tag{6a}$$

$$u_3 = \cos r \tag{7a}$$

concentric projection

$$r = (X^2 + Y^2)^{1/2}/F \tag{4b}$$

$$u_1 = (X \sin r)/(F\ r) \tag{5b}$$

$$u_2 = (Y \sin r)/(F\ r) \tag{6b}$$

$$u_3 = \cos r \tag{7b}$$

iii) For an object occurring on plate A and in the reference catalogue we have the three equations

$$\xi_i + \varepsilon_i = \sum_j a_{ij}{}^A \quad u_j{}^A \ , \ i = 1,2,3 \tag{8}$$

while for an object occurring on the plates A and B we find

$$\varepsilon_i = \sum_j a_{ij}{}^A\ u_j{}^A - a_{ij}{}^B\ u_j{}^B \ , \ i = 1.2,3 \tag{9}$$

Here the matrices may be expected to be nearly orthogonal (they will be in the absence of field distortion and accidental errors). It is our purpose, then, to determine the matrix elements $a_{ij}{}^M$ with i, j = 1,2,3 and M = 1,2,3....N. N is the number of plates to be treated simultaneously. We obtain a unique solution by imposing the three equations

$$\sum (\varepsilon_i)^2 = \text{minimum},\ i = 1,2,3 \tag{10}$$

The leads to three systems of 3N linear equations with a common square matrix and three different solution vectors.

THE COMPUTER PROGRAM RAA

The subprogram flow of RAA is shown in Fig. 1, together with an explanation of the symbols used. The function of the subprograms are as follows:

1. RD is a data reading program. It receives the data either from punchcards, or from tape, disk, diskette, or directly from the keyboard, and stores them in the datafile 01. The data stored are

plate No., star No., X, Y, magnitude or photographic density or blank.

2. LM reads for each plate the rectangular coordinates of the tangential point or the plate center as well as provisional values of the matrix elements. These can be obtained from a separate program (Protan or Procon) which determines the matrix from a few stars for which α, δ, X, Y are known, as well as an approximate value of the scale factor F. The latter may be different from plate to plate. This permits mixing plates from different telescopes. The data are stored in the data file 05. The data stored are, in sequential order

plate No., plate scale, X, Y of plate center, nine matrix elements.

3. IM reads 05 and produces the inverse matrices b_{ij}^{A} for all plates. These are stored in the data file 06 the same way as the data in 05.

4. AD reads the data files 01 and 05 and converts all X, Y into α and δ. The program will reject all stars coded as rejects, or for which no provisional maxtrix elements are known. This program will either forward magnitudes to the next data file, or convert densities into magnitudes by a multi-linear conversion, and forward these. The data are stored in File 02 and they are

plate No., star No., α(hours and fractions), δ(degrees and fractions), mag, weight (=1)

As may be seen here, a weight 1 is introduced in order to enable the operator to eliminate objects in file 02 or in the following data files by assigning a weight zero.

5. RC will read reference star data and store them in file 03. Data stored are

star No., mag., α (h,m,s, proper motion), δ ($^{\circ}$,$'$,$''$, proper motion)

6. EP reads file 03 and with the keyboard entered epoch difference produces α and δ for the desired epoch. The data are stored in file 04 which has the same format as file 02.

7. MG merges files 02 and 04 and stores them in file 07 (format

same as 02).

8. OR arranges the content of file 07 in order of ascending Right Ascension. Data are stored in file 08 (format as for file 02).

9. ID reads file 08, identifies common objects, and separates them into groups. For this purpose the operator enters the tolerances in Right Ascension and Declination through the keyboard. Data are stored in file 09 (format as before).

10. BL is the heart of RAA. It reads files 09 and 06 and recovers star by star the original u-values, making use of the respective inverse matrix, then applies equations (8), (9), and (10), producing the 3N by 3(N+1) matrix to be stored in file 10.

11. SM resolves the matrix stored in file 10, calculates the 3N coefficients and stores them in file 11.

12. TM prints the matrices, plate by plate, together with the respective plate centers calculated from the elements of the third column of a_{ij}^M, as well as the sum of the squares of each column (as a check on major scale errors).

13. AN analyzes file 09. It prints the numbers of all reference stars not found on any of the plates. Also it makes link statistics. It will tell, how many stars occur only once, how many on two plates, etc.

14. EN also analyzes file 09. It will print the number of stars common to any pair of plates, as well as how many reference stars were found on each plate. This program, as well as the previous, will tell whether the tolerances in step 9 (ID) were well chosen. If too small, too few links will be found. If too large non-identical stars will be collected into one group. Thus one may find stars which have been measured more times than there are plates.

15. PP reads files 09, 06 and 11. Group by group, and within a group star by star, it recovers the u-values with the help of file 06, calculates new coordinates using file 11, averages the Right Ascension and Declination and the magnitudes, and prints the final positions and magnitudes with their respective mean errors.

At this point the process may be recycled. From file 11 we may produce an improved version of file 05, retaining the previous file 06. Thus we enter again at the fourth step with AD, reproducing all subsequent files with the exception of file 04, skipping also steps 5 and 6. A recycling makes sense if one may expect that better coordinates will produce more links in step 9. If not, then file 11 contains the final set of plate matrices.

APPLICATIONS

We have applied RAA to two different sets of data, namely to nine overlapping plates of the Cape Zone of the CdC (Gill, 1913), and to fifteen plates taken recently with the CIDA-Refractor of the open cluster Tr10. The area of the CdC that was chosen is centered on the same object. A total of more than 6000 stars with about 9600 entries in the CdC was processed. Of these, 2826 stars are in the overlap area and the respective position catalogue (equinox 1950.0 and epoch 1901.5) can be made available in machine output form. In the case of the Refractor plates, a total of about 5600 entries were processed. These led to a position catalogue (equinox 1950.0 and epoch 1982.4) for 982 stars which will be published shortly.

Not counting the large amount of time spent in keying the CdC and Refractor data into the computer, and entire RAA-cycle took somewhat more than two hours on a Nova 3 computer with 64K memory for both examples. Of this, nearly 40% is used by the ordering program OR, the efficiency of which depends totally on the memory size. The next in time consumption is BL. In this case the time consumed does not depend on the memory size. However, the maximum number of plates that can be processed simultaneously depends on the memory size. In our case 15 plates is the maximum.

REFERENCES

Gill, D., 1913, Cape Astrographic Zones, Vols. I, II, and III.

Stock, J., 1981, Rev. Mex. Astron. y Astrof., 6, 115.

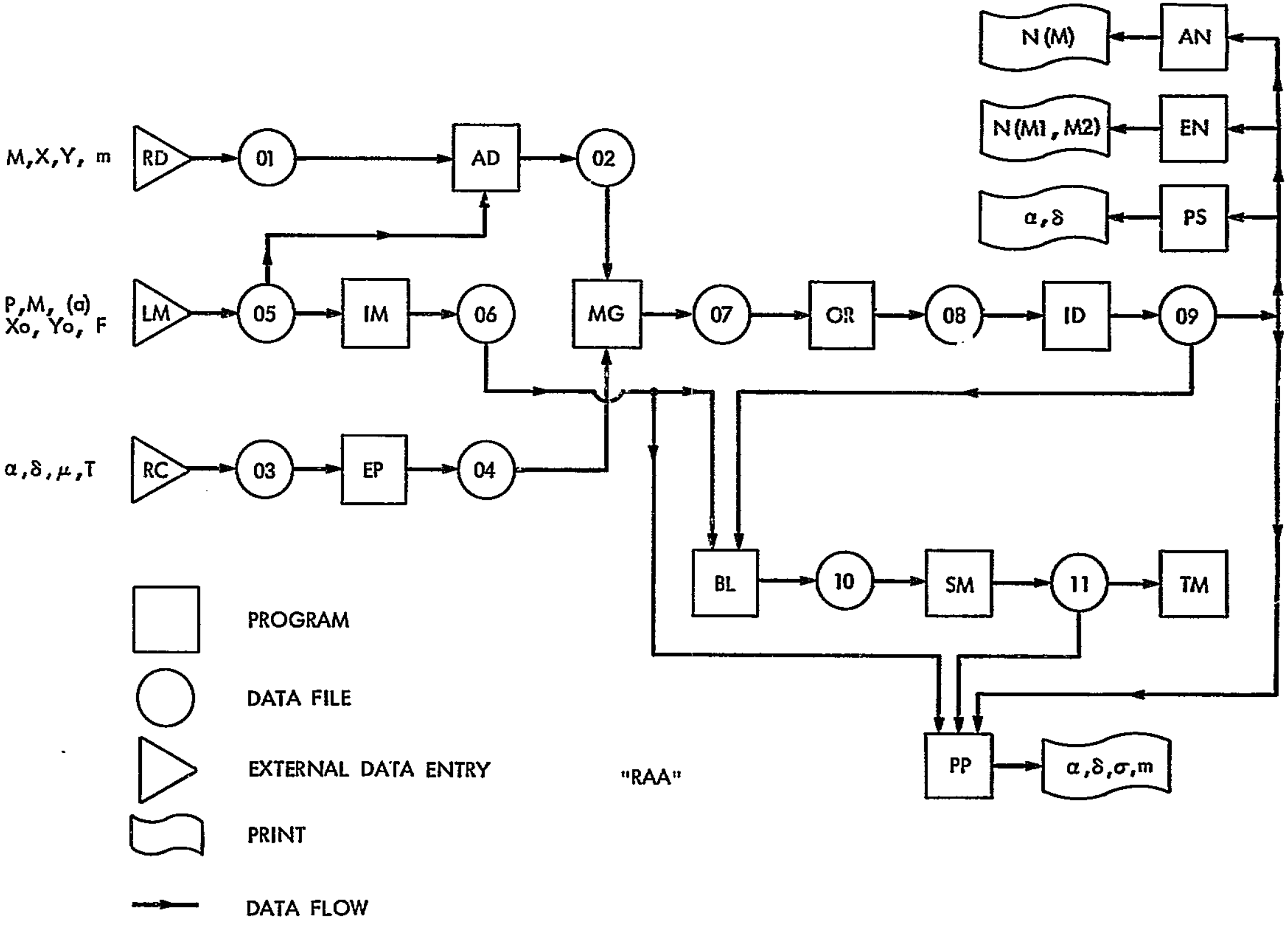

Figure 1. RAA subprogram flow

N85-25034 D19

OCCULTATIONS OF STARS AND RADIO SOURCES BY COMETS: PREDICTIONS AND OBSERVING PROSPECTS

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ABSTRACT

We outline the results that might stem from observations of occultations of stars and radio sources by cometary comae and ion tails. Taking account of the current orbital accuracy of P/Halley, we present specific predictions of stellar appulses with that comet, including preliminary topocentric circumstances. A crude model of the absorption of starlight by grains in a "dusty" comet gives us reason to believe that stellar extinction may be observable in practice. Thus, we set down some thoughts on observing techniques, discussing the merits of a two-dimensional detector (a CCD camera) and a conventional aperture photometer. We stress the need for accurate photometric observations with time resolution ≤ 1 sec, because the interval of greatest extinction will usually be brief. Finally, we explore the efficacy of undertaking accurate relative astrometry of comets during predicted approaches to stars.

GOALS

In principle, the occultation of a star or radio source by a comet provides a unique method of probing important properties of the coma and tail, at high spatial resolution, by a variety of observational techniques.

- Photometric observation of any diminution of the starlight passing through the inner coma would give a direct measurement of the grain distribution as a function of nuclear distance, from which the albedo of the grains could be inferred if the surface brightness of the coma along the line of sight was known (Combes et al. 1983).

- Observation of the occultation of a star by a cometary nucleus would give information on the diameter of the nucleus and perhaps, because of refractive attenuation, on gas very near the surface of the nucleus.

- High-resolution spectroscopy at visual and infrared wavelengths may serve to detect absorption lines of otherwise undetectable gases in the coma (Barry L. Lutz 1984, private communication).

- Radio observations can yield the electron density distribution in the plasma tail (Wright and Nelson 1979; de Pater and Ip 1983).

- Moderately close appulses of a comet with stars afford a means of carrying out accurate relative astrometry of the comet, especially if its nucleus is detectable.

In this paper we emphasize results that might derive from observations of P/Halley, although most of the considerations could apply to other comets. We outline our method of predicting comet-star and comet-radio source appulses and give some specific predictions for P/Halley. We discuss anticipated results and their modelling, and describe observational techniques that might be used to monitor the changing brightness of stars occulted by comets. Finally, we examine a technique of carrying out accurate relative astrometry of comets.

PREDICTIONS

Predictions of comet-star and comet-radio source appulses are made by comparing cometary ephemerides with star and radio-source catalogs and flagging all appulses for which the closest comet-source geocentric separation is smaller than a specified threshold.

Search Procedure

Our usual search procedure, developed initially by Wasserman and Bowell for occultations of stars by asteroids, has been described by Wasserman et al. (1981). Since the procedure used for most comets differs only in detail from that used for asteroids, we give only a brief step-by-step summary here.

- Chosen osculating elements of the comet are integrated numerically using, typically, a two-day timestep. Perturbations by all nine planets are taken into account, as are non-gravitational forces radial and tangential to the comet's motion.

- Orbital elements at each timestep are used to generate a 0.2-day-interval ephemeris.

- The resulting eleven geocentric positions define an area on the plane of the sky that we map in (ξ,η) standard coordinates.

- A chosen star or radio-source catalogue, stored on a disk, is searched, and records of sources located in the region of interest are abstracted.

- The source positions, corrected for proper motion if necessary, are transformed into (ξ,η) coordinates for direct comparison with the comet's ephemeris.

- The two-day interval is divided into five abutting segments, each containing three ephemeris positions that are represented by quadratic functions of ξ and η.

- The closest approach distance of the comet to each source is calculated. This method allows for changes from retrograde to prograde motion (and vice versa) of the comet, and thereby permits prediction of an appulse in the vicinity of a "stationary" point and in the extremely rare instance when two appulses of a given source occur within two days.

- Sources whose geocentric separations from the comet are smaller than a specified threshold are abstracted for further processing.

- The orbit integration is advanced step by step, and the entire procedure is repeated until the desired end date is reached.

As well as searching conventional star catalogues, we have developed the technique of identifying the passage of comets in front of open star clusters, where enhanced opportunity to observe close appulses can be expected. An additional technique for identifying appulses with stars consists of using a scanning microdensitometer to track across a photographic plate, following the comet's apparent path in the sky; this method has been successfully applied to the study of occultations of stars by asteroids (e.g., Millis *et al*. 1983).

Selected Predictions for P/Halley

Using "Orbit #12" by Donald K. Yeomans, Bowell and Wasserman (1984) have identified appulses of P/Halley with stars and radio sources. The star catalogue used was the *Official International Halley Watch Preliminary Reference Star Catalog* supplied by Robert S. Harrington. This catalogue contains star positions derived from the AGK3 and SAO catalogues, together with positions from plates taken at Lick Observatory and from the so-called Moscow catalogue. Since the IHW catalogue is evolving with time and since improvement of P/Halley's orbit may be expected, we plan to issue updated lists of appulses, through the auspices of the IHW, as appropriate. For occultations of stars, we assumed a coma diameter of 45,000 km (approximately 1 arcmin at 1 AU), and an appulse was logged if the minimum geocentric star-comet separation was less than the apparent angular radius of the comet plus twice the equatorial horizontal parallax, or 5 arcsec, whichever was greater. Taylor (1984a) has made similar predictions for P/Halley, but his work is based on an earlier orbit for the comet and he considers only early-type stars.

For predictions involving radio sources, we used the *Master List of Radio Sources*, updated from Dixon (1970). For our purposes, we combined all duplicate entries in that catalogue. Rather than attempt to model the extent and direction of P/Halley's ion tail, we simply specified a very large cometary diameter of 1,350,000 km (approximately a 30-arcmin diameter at 1 AU) for the identification of appulses. The accuracy requirements for radio-source occultations are far less stringent than those for stars, so the radio-source predictions should not need to be updated.

Orbital accuracy. We have tried to estimate the present accuracy of P/Halley's ephemeris by comparing positions computed from a number of available orbits on chosen dates throughout the upcoming apparition. As would be expected, the maximum ephemeris discrepancies occur close to the times of perihelion (1986 Feb 09) and closest Earth approach (1986 Apr 10). Figure 1 illustrates the situation at perihelion. Five predicted ephemeris positions, from five orbits, spread along a line 2 arcmin in extent. Unaccountably, the direction of this line corresponds neither to the line of variation nor to the geocentric motion vector (the same situation prevails at other times). If P/Halley's ephemeris uncertainty were in the direction of the motion vector, then, in the absence of other errors, the comet-source separations observed would be very similar to those predicted but would occur at different times. Thus, for a central occultation, the ground track would be displaced more or less along itself. However, in view of the results of the ephemeris calculations, we must conclude that ground tracks predicted at present may be in error both in time and topocentric location.

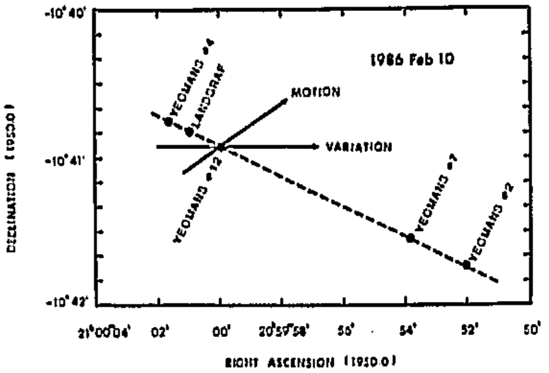


Figure 1. Uncertainty in the ephemeris of P/Halley near perihelion.

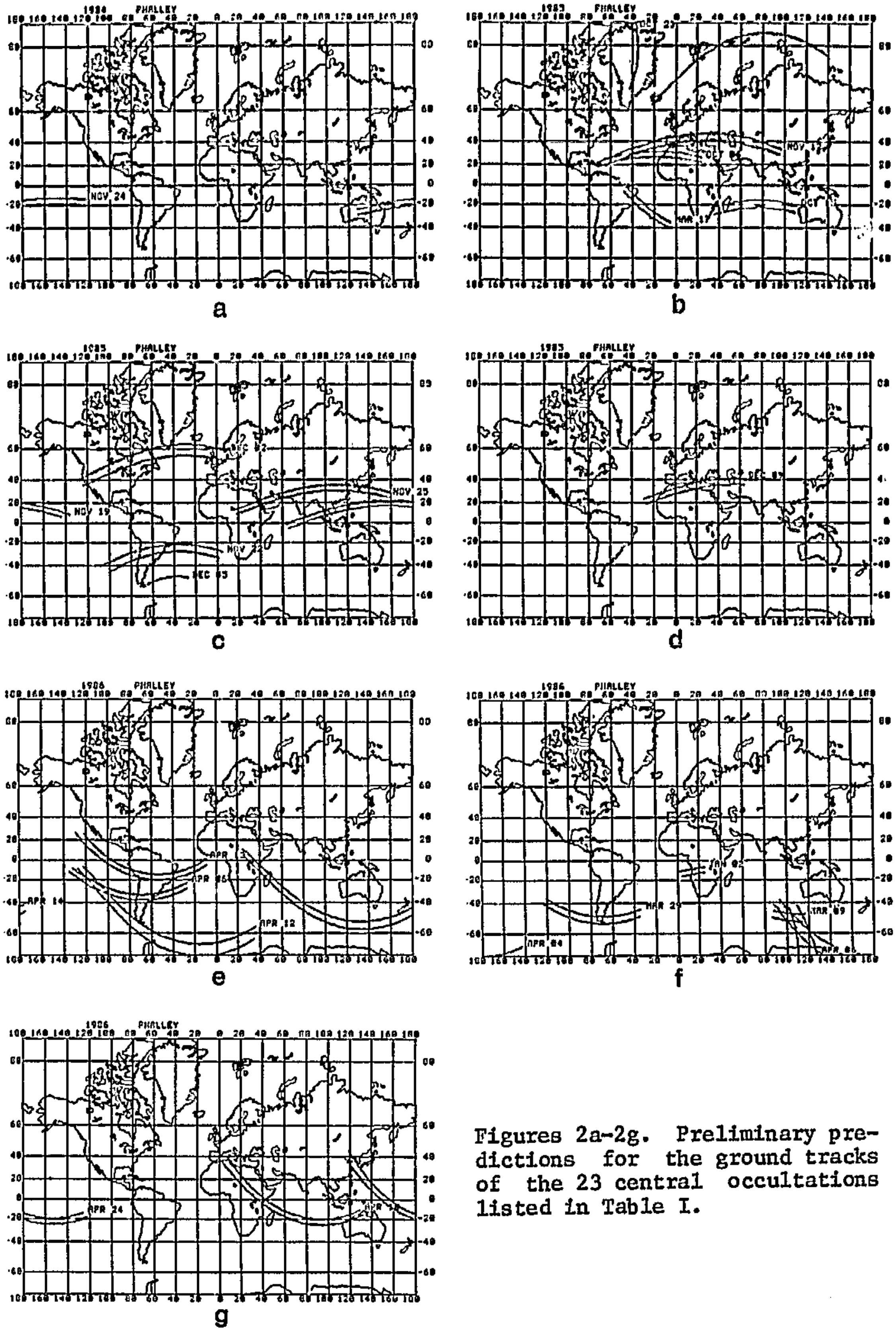
Given the 2-arcmin spread in ephemeris predictions, as depicted in Figure 1, and the fact that a cometary ephemeris error of only 1 arcsec leads to an error on the ground of 725•Δ•sec z km, where Δ is the observer-comet distance in AU and z the observed zenith distance of the comet, one may perhaps be justifiably pessimistic about the usefulness of present predictions. (Of course, errors in star catalogue positions introduce similar uncertainties as well.) However, there are two considerations that lead us to believe that specific topocentric predictions can indeed be usefully made now: (1) the most recently derived orbits (particularly orbit #12 of Yeomans and that of Landgraf 1984) result in ephemerides that differ by less than 2 arcmin at worst; (2) the ephemeris uncertainty peaks very strongly at perihelion and close Earth approach. Predictions based on the five orbits used in Figure 1 show that, throughout most of the apparition, uncertainties of only a few arcsec can be expected.

Predicted ground tracks. Circumstances for stellar appulses of P/Halley that we believe might lead to central occultations observable somewhere on Earth are listed in Table I. Star numbers are either four-digit sequential numbers from the IHW catalogue or are BD designations. The minimum comet-star separation and transverse velocity are geocentric. The star and comet magnitudes are photographic, the latter being taken from Yeomans (1983).

Figures 2a through 2g illustrate the ground tracks of the central occultations. For purposes of presentation, we have arbitrarily assigned a diameter of 500 km to the central region of P/Halley. Ends of tracks correspond to places on Earth where the Sun and comet are on the horizon. In all cases, occultations proceed westward on the Earth's surface. The southern limits of the events on 1985 December 5 and 1986 April 4 are predicted to miss the Earth. In view of the comments (above) on prediction accuracy, we suppose that cross-track uncertainty may amount to 2000 km or more throughout most of the apparition, being even

Table 1. Possible central occultations of stars by P/Halley between 1984 June 30 and 1987 July 1

Star number	Minimum separation (arcsec)	Geocentric conjunction (E.T.)	Transverse velocity (km/s)	R.A. (1950.0) (Epoch of event)	Dec.	Δ (AU)	Star mag	Comet mag		Sun	Moon	
								Total	Nuclear	elong. (deg)	elong. (deg)	illum. (%)
6576	0.9	1984 Nov 24.53237	29.3	$6^h 23^m 52^s.737$	+11°58'05".10	4.783	13.6	-	21.3	144.4	161.1	3.3
3716	0.3	1985 Mar 17.92008	7.4	4 51 39.410	+14 16 01.74	4.686	13.0	16.1	20.7	76.6	115.3	11.9
8462	0.3	1985 Oct 06.14915	8.2	6 09 05.252	+20 12 05.28	1.876	13.5	10.8	17.3	100.2	7.6	60.5
8172	3.8	1985 Oct 15.89373	14.6	6 00 08.441	+20 40 34.79	1.561	13.9	10.2	16.8	111.9	135.8	4.4
7705	6.0	1985 Oct 23.86545	20.9	5 46 18.564	+21 11 25.80	1.312	14.1	9.6	16.3	123.1	110.6	79.4
+21°0616	4.1	1985 Nov 12.96851	42.8	4 14 38.661	+22 08 16.89	0.776	9.2	7.7	14.8	164.3	169.4	0.2
+20°0531	0.6	1985 Nov 19.59677	50.1	3 13 08.527	+20 51 12.23	0.666	8.2	7.1	14.3	174.1	82.5	52.4
+19°0424	10.0	1985 Nov 22.12466	52.0	2 45 30.189	+19 48 09.47	0.640	8.3	6.8	14.2	165.3	44.8	76.1
1511	2.7	1985 Nov 25.71176	53.2	2 04 21.497	+17 42 04.39	0.621	11.1	6.6	14.1	151.8	9.3	97.1
+12°0114	8.2	1985 Dec 02.08083	50.2	0 54 11.129	+12 45 31.69	0.638	10.0	6.3	14.0	127.8	101.8	81.7
+9°0046	12.9	1985 Dec 05.09276	47.2	0 25 24.438	+10 18 17.32	0.667	10.6	6.3	14.0	117.3	147.0	53.2
+6°5207	3.3	1985 Dec 09.82843	41.5	23 47 35.098	+06 46 09.04	0.732	9.1	6.2	14.1	102.5	133.4	7.2
-3°5403	3.8	1986 Jan 02.79992	22.2	22 10 43.515	-02 58 53.45	1.194	9.0	5.8	14.4	52.4	152.8	61.4
-20°5852	0.5	1986 Mar 09.86659	21.9	20 09 53.497	-19 54 53.84	1.064	9.0	4.5	13.9	48.2	39.3	0.7
-35°12981	1.0	1986 Mar 29.31488	38.9	18 48 54.287	-35 12 45.32	0.584	8.2	4.2	13.2	87.7	49.7	86.4
-43°11763	7.8	1986 Apr 04.61424	50.2	17 26 51.916	-43 42 57.56	0.465	7.5	4.0	12.9	109.1	56.3	21.2
-45°8209	4.1	1986 Apr 06.30077	52.8	16 53 01.990	-45 39 55.19	0.444	9.6	4.0	12.8	115.9	83.0	8.8
-45°8176	13.5	1986 Apr 06.49764	53.1	16 48 42.163	-45 51 15.46	0.442	9.8	4.0	12.8	116.7	86.2	7.7
-45°6861	7.1	1986 Apr 12.13757	56.9	14 25 48.436	-46 05 52.16	0.419	9.0	4.0	12.9	139.6	152.2	7.6
-44°6616	10.5	1986 Apr 13.24168	56.3	13 58 48.547	-44 47 44.93	0.425	9.5	4.1	12.9	143.2	145.7	14.1
-42°6280	2.7	1986 Apr 14.72181	54.9	13 26 02.498	-42 31 48.00	0.437	9.6	4.2	13.0	146.8	128.6	25.1
-34°8087	7.6	1986 Apr 18.82197	48.3	12 17 58.398	-34 57 18.18	0.495	9.3	4.6	13.3	148.9	71.7	63.8
-25°8682	6.3	1986 Apr 24.49723	38.1	11 25 08.642	-25 35 06.97	0.622	6.8	5.3	13.9	140.3	39.1	100.0



a b c d e f g

Figures 2a-2g. Preliminary predictions for the ground tracks of the 23 central occultations listed in Table I.

larger near the times of close Earth approach in November 1985 and April 1986. The reader may draw his own conclusions about the feasibility of observing a given event from his locality. We remark only that there is little likelihood that any star brighter than B ~ 7 mag will be occulted centrally.

Refinement of predictions. Experience in predicting occultations of stars by asteroids has underscored the necessity of obtaining accurate astrometry of both asteroid and star within a few days of the event (Millis and Elliot 1979). We have found that relative astrometric accuracy for asteroid-star appulses of ~0.05 arcsec is achievable, which leads, typically, to cross-track uncertainties of ~100 km on the ground. Such accuracy will rarely be realized for comets, except during close approaches to Earth, because of their diffuseness and the resulting difficulty of precisely locating the nucleus or point of peak brightness in the coma. Furthermore, the astrometric problem will be exacerbated for P/Halley during most of the interval between about October 1985 and May 1986, when the comet will be moving across the sky at more than half a degree per day. Thus, it will not be easy to photograph comet and star on a single plate using the narrow-field astrographs required to give high astrometric accuracy. It seems, at best, that only "last-minute" refinement of the ground-track location can be achieved. But even if the relative star-comet astrometric accuracy is as poor as 1 arcsec, it will be possible to predict the path of the comet to within a few hundred kilometers near the time of closest Earth approach. Therefore, the astrometric constraints should not be viewed as a serious deterrent by potential observers.

ANTICIPATED EXTINCTION

Several detections of diminution of starlight during cometary appulses have been reported (Dossin 1962; Combes et al. 1982; Nolthenius 1983; Larson and A'Hearn 1984; Marino and Walker 1984). However, skepticism has been expressed about many of the observations, in part because most of the stars involved were very faint, resulting in poor signal-to-noise-ratio data. Dunham and Goguen (1983) have gone so far as to argue that detection of a measurable change in stellar brightness during a comet occultation is effectively impossible. That we do not share their pessimism should be clear from the following sections.

A Crude Model

We have modelled the attenuation of starlight by grains in a cometary coma. It is clear that, except for relatively dusty comets at heliocentric distances $r \lesssim 2$ AU, the attenuation of an occulted star is likely to be extremely small and undetectable unless the appulse is extraordinarily close. We use the term "dusty" as the customary label for comets whose brightness is high in the spectral continuum relative to that due to gaseous emission. Our estimates of the optical thicknesses to be expected are based on the absolute photometry of several comets by A'Hearn and Millis (1980), on the nature of the surface brightness profiles of comae (Baum et al. 1983), and on the single-particle phase function derived from observations of C/West by Ney and

Merrill (1976). We assume that coma particles are in the far field, i.e., they do not cast shadows on one another and multiple scattering is negligible.

The intensity of light scattered toward the observer by a single particle, assuming a Henyey-Greenstein model, is

$$I = \frac{\omega_0 F}{4\pi} \frac{1-g^2}{(1+g^2+2g \cos \alpha)^{3/2}},$$

where ω_0 is the single-scattering albedo, F the incident solar flux, g the asymmetry factor, and α the solar phase angle. Fitting to Ney's and Merrill's data, we find that $g \sim +0.5$, indicating that particles are strongly forward scattering. A better fit could doubtless be achieved with the sum of two Henyey-Greenstein functions or with a different single-scattering function such as that derived for zodiacal-light particles by Lumme and Bowell (1984a); but the present calculation need only be approximate. Ney's and Merrill's observations also imply that $0.3 < \omega_0 < 0.5$, so we choose $\omega_0 = 0.4$; but, as Hanner et al. (1981) have pointed out, calculations of albedo are very model-dependent. For a tenuous cloud of coma particles, the optical thickness τ is then given by

$$1-e^{-\tau} = \frac{(1.25 + \cos \alpha)^{3/2}}{0.0239} R,$$

where R is the reflectance derived from observations of the coma's surface brightness.

Among the comets discussed by A'Hearn and Millis (1980), the dustiest was C/Meier. When that comet was at $r = 2.55$ AU and at $\alpha = 16.4$ degrees, their data imply $R = 0.000133$ at a nuclear distance $d = 100$ km, from which we predict $\tau \sim 0.018$, corresponding to a 0.02-mag attenuation of starlight. From a different line of reasoning, deriving from the work of A'Hearn et al. (1984), A'Hearn arrives at estimates in the same general range (Michael F. A'Hearn, private communication). If the same comet could have been observed at a substantially smaller heliocentric distance, however, the dust production and therefore the optical thickness would have been very much greater. To judge from the observed dependence of C/Meier's brightness on heliocentric distance (Meisel and Morris 1982), its attentuation of an occulted star when at $r = 1.5$ AU would have been roughly 1.1 mag at $d = 100$ km and 0.02 mag at $d \sim 5000$ km. (We make use of the expectation that the surface brightness of the innermost coma varies as $1/d$. Although mathematical models for the acceleration of grains by radially expanding cometary gas (reviewed by Wallis 1982) imply a departure from the $1/d$ dependence very near the nucleus, that departure is likely to be small within the range under discussion.)

We have also modelled the scattering of starlight by cometary grains, insofar as it would affect the interpretation of observations. The effect of diffraction is negligible. Thus the amount of starlight scattered by coma particles at small angular distances from the star can be completely ignored; clearly, the effect is even smaller than that of diffraction. Likewise, transmission of starlight through grains is negligible. Even for rather transparent grains, the amount of starlight transmitted directly toward the observer will be very small. The overall result of these considerations is that obstruction of starlight by grains, together with the scattering of sunlight, should follow the laws of geometric optics rather closely. Thus, if the attenuation of starlight and the brightness of the corresponding region of the coma can be observed simultaneously, then the column density of grains and their mean geometric albedo may be calculated in a straightforward way. Further details of the modelling of observed extinction will be given by Lumme and Bowell (1984b).

In addition to the attenuation of starlight by cometary grains, there is another phenomenon we thought it wise to evaluate, namely, refractive dimming by gas. The phenomenon is analogous to that encountered when a star is occulted by the atmosphere of a planet, but the geometry is different because the coma of a comet is not an exponential atmosphere with a scale height small compared with the radius of the solid body. We have worked out a theoretical model for refractive dimming of starlight by a cometary coma. We find that the expected dimming varies approximately as $1/d^3$ and that it will certainly be negligible for all comets if $d > 20$ km. Owing to the $1/d^3$ dependence, however, refractive dimming may dominate within a kilometer or two of the nucleus. If we are ever so fortunate as to record an occultation by the nucleus itself, the apparent occultation diameter may therefore be larger than the body itself, and the occultation lightcurve, rather than having a quasi-instantaneous immersion and emersion profile, may have a shape that provides information about the gas as well as the grains.

P/Halley

We have not attempted to model the dust-production regime of P/Halley specifically, feeling that there are at present too many unknown factors. However, a few optical properties can be adduced from the results of our model of a dusty comet (above) and the work of others. P/Halley is likely to be moderately dusty (Zdenek Sekanina 1984, personal communication). Using Newburn's (1979) work on 1910 observations of P/Halley, Hellmich and Keller (1981) computed a continuum optical depth of about 0.6 in the direction of the nucleus at the time of the Giotto spacecraft flyby. Thus, close to the nucleus the optical depth of the coma may amount to $\tau \sim 1.2$, in general agreement with our estimate for C/Meier, a dustier comet. Divine (1981) has also modelled the scattering and absorption of light from grains in P/Halley's coma, although only for a specific observing geometry at a time near perihelion. He derives a Bond albedo for grains of 0.3, whence a geometric albedo of 0.065. Further modelling leads him to conclude that $\tau = 0.14$ in the direction of the nucleus. Just as we do, however, all the authors stress the uncertainty of their results.

OBSERVING TECHNIQUES

In this section we remark on techniques that might be used to monitor the brightness of a star as its light is dimmed by occulting cometary grains. First considerations are:

- To maximize the contribution of starlight to the total signal, one should observe in the comet's continuum, away from emission lines and bands. For comets with little gaseous emission, suitable readily available broadband filters are Strömgren v (4110 Å, FWHM 200 Å) and six-color R (7000 Å, FWHM 200Å). If bright stars are involved or large telescopes available, then it will be advantageous to use narrowband filters that isolate the continuum, such as those of the IAU standard comet filter set. Whenever possible, a filter should be selected so as to maximize the stellar flux. Contrary to the statement by Taylor (1984a), the presence of stellar absorption features is irrelevant to the study of cometary grains, so it is not necessary to observe only early-type stars.

- Collaboration among observers would be very useful. At a given location, the apparent path of the star sweeps out a chord across the coma. Thus, if observers are able to deploy themselves, perhaps using portable equipment, at different distances from the predicted centerline of the ground track, then large volumes of the coma could be mapped.

- In view of the uncertainties in astrometry and dust-production rates, observers should be prepared to encounter an occultation lightcurve of unexpected form. For example, a central occultation may occur even though the predicted center line of the ground track is several hundred kilometers distant. In particular, they should be aware of the anticipated time scale of the event, as is emphasized below.

If we are correct in supposing that dusty comets can produce substantial stellar extinctions, at least close to the nucleus, then observed lightcurves may resemble those sketched in Figure 3. The curves represent idealized, noise-free observations of a dusty comet of the kind we modelled in the previous section (also, distances for the closest approach to the nucleus are indicative only). The following remarks are keyed to the letters in Figure 3:

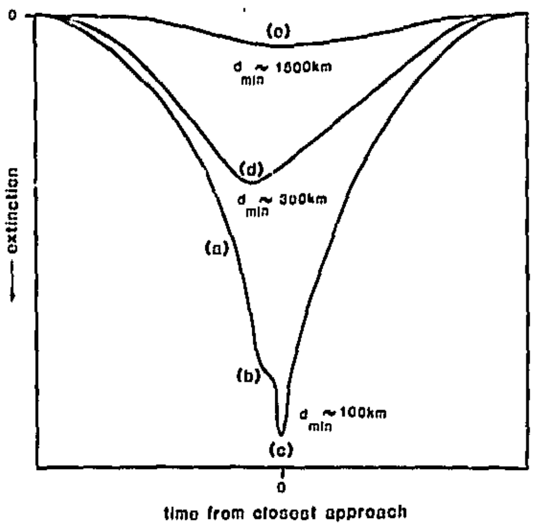


Figure 3. Anticipated extinction of starlight as a function of time for different minimum line-of-sight distances from the nucleus.

(a) For a near-central occultation, the drop-off in the star's brightness will most likely follow a 1/d dependence, just as the brightness of the coma increases toward the nucleus.

(b) Close to the nucleus one might expect to detect enhancements in particle density caused by jets and sudden outgassing events. According to Larson and Sekanina (1984), there was evidence for increases of a factor ≥ 2 in the column density of dust in jets close to the nucleus of P/Halley in 1910.

(c) The region of maximum extinction will be traversed rapidly.

(d) Could one detect large-scale inhomogeneities in the column density of grains at somewhat larger nuclear distances, resulting in asymmetric lightcurves?

(e) Very shallow extinctions are expected farther from the nucleus.

Since we cannot claim to be able to predict the amount of extinction observable during an occultation by a given comet, it may be that some or most of the particular phenomena outlined above are unobservable in practice. We can, however, specify the time scale on which stellar extinction is expected, because the line of sight to the occulted star sweeps across the coma at a rate equal to the transverse velocity of the comet with respect to the observer. For P/Halley, a rather extreme case, this velocity exceeds 50 km/sec in November-December 1985 and April 1986 (cf. Table I). Thus, for a central occultation at that time, the main observing activity will be limited to a few seconds. Occultation by the nucleus will last only about 0.1 sec. Optimistically, we anticipate that the entire observable lightcurve will be recorded in about three minutes. Clearly, the rapidity of such events places severe constraints on the kinds of photometric monitoring achievable and imposes stringent requirements on observing technique.

We discuss some of the merits of observing with a two-dimensional detector (a CCD camera) and a conventional aperture photometer in the following subsections.

CCD Observations

Larson and A'Hearn (1984) have described, in some detail, observations of the occultation of a 15th-magnitude star by C/Bowell on 1982 April 26. The comet's transverse velocity was 7.2 km/sec, and five 30-second exposures were made at nuclear distances ranging from 530 to 4030 km, all well within the visible coma. The time-dependent brightness of the occulted star was determined by subtracting the known brightness distribution of the merged comet image and normalizing the star's brightness to that of a nearby field star.

The advantages of using a CCD camera in the general case are clear:

- The light distribution within the coma may be modelled by exposing frames before or after the occultation. These data can be used both to estimate the occulted star's brightness at times when the comet and star images are merged and to provide a two-dimensional map of the coma for final analysis of the observations.

- Variations in sky brightness and transparency can be compensated for if a nearby field star is available to serve as a photometric reference.

Combes et al. (1983) have stressed the efficacy of making serendipitous observations of the occultations of faint stars by comets using a CCD camera. They calculate that, in the average case, about one event per night might be observable for comets moving in the galactic plane. We are less optimistic, as the following calculation shows. We derive

$$\nu = 38\mu \frac{d}{\Delta} N_V,$$

where

$$\log N_V = 3.42 + 0.39\,(V_{lim}-15) - [0.024 + 0.008\,(V_{lim}-15)]|b|;$$

$$12 \lesssim V_{lim} \lesssim 18 \text{ mag}; \; 0° < |b| \lesssim 40°.$$

Here ν is the expected average frequency of appulses, per eight-hour night, within a minimum nuclear distance d km, for a comet at distance Δ km moving μ deg/day in the plane of the sky. N_V is the number of stars per square degree brighter than V_{lim} mag at galactic latitude b degrees (from Allen 1973). Choosing $\mu = 0.5$ deg/day, $d = 2000$ km, $\Delta = 1$ AU, $V_{lim} = 16$ mag, and $b = 0°$, we obtain $\nu = 1.6$ occultations/eight-hour night, in substantial agreement with the estimate by Combes et al. However, the results from our crude model (above) indicate that it is probably more appropriate to restrict observations to much smaller minimum nuclear distances, and that, because of the brevity of the observable part of an occultation, a brighter V_{lim} should be adopted. Thus, with $d = 200$ km and $V_{lim} = 15$ mag, we obtain $\nu = 0.07$ occultations/eight-hour night. In the average case ($|b| = 30°$), $\nu = 0.01$ occultations/eight-hour night. Thus, one probably should not expect to reap a bountiful harvest of serendipitous occultation observations unless an exceptional comet is observed. A further impediment to serendipitously observed occultations is the uncertainty, at the outset of the observations, that a near-central occultation will actually occur. Many hours of large-telescope time could thereby be squandered. Obviously, close to the estimated time of closest approach, one should observe near-continuously.

Referring specifically to observations of P/Halley, we comment as follows:

- The rapidity of the central portion of most occultations would make it necessary to use short exposures. Clearly, it will be desirable to expose more frequently than the full-frame readout time (typically, many seconds). This might be accomplished by reading out subframes of the whole image, perhaps by using a multiple-exposure method in which the image is shifted quickly while the shutter is closed between exposures, or by exposing continuously on a deliberately trailed image.

- It will not be practicable to make serendipitous observations of occultations of faint stars throughout most of the apparition. Assuming d = 200 km and V_{lim} = 15 mag, we calculate that $\nu < 0.02$ occultations/eight-hour for much of the apparition. At the close approach in November 1985, ν = 0.08 occultations/eight-hour night, and at that of April 1986, ν = 0.2 occultations/eight-hour night.

- Nearby field stars, to be used as photometric references, will most likely not be recorded if short exposures on a bright star are used. However, providing sky conditions are stable, raw star magnitudes should be sufficiently accurate, at least during the central phase of an occultation. Alternatively, it may be possible to use the modelled integrated light of the coma to standardize the star photometry, though presumably with loss of accuracy.

Aperture Photometry

During the close appulse of a comet with a star, a one-dimensional photoelectric photometer will record the sum of the light from both objects plus that due to the sky background and any other field objects. Thus, to maximize the signal-to-noise ratio of the starlight, a small aperture should be used, though naturally one should follow good photometric practices by assuring that the star's light is fully contained in the aperture. Usually the outer regions of the coma will overflow the aperture, in which case poor registration of the aperture and the coma will lead to apparent brightness fluctuations that are not necessarily ascribable to the occultation. Clearly, special precautions are necessary. The following remarks may be useful to observers.

For a small comet or one that is centrally condensed, one could use a circular aperture selected to contain all or most of the light from the coma (this could be done by experiment before the occultation). Centering and guiding on the star, the comet would be seen to move across the aperture. If there is any effect due to the coma's light not being entirely contained within the aperture then, unless the coma is quite asymmetric, the photometric error will be minimized at closest approach because one flank of the coma will be entering the aperture as the other is leaving it.

For some extended comets, it seems to us more desirable to guide on the comet and to allow the image of the occulted star to pass through the aperture. Thus, in steady observing conditions, while the star's light is fully contained in the aperture, any brightness variation can be ascribed to an occultation. This method may only work well when the nucleus or central condensation is clearly visible so that accurate guiding is possible. Advantages are that the level of brightness fluctuation due to imperfect guiding can be estimated by experiment prior to the event and that the aperture size might be quite small compared to the total extent of the coma.

For large and diffuse comets, it may be necessary to track on the star, using a small aperture that does not contain the entire coma. In this case the brightness of the coma along the apparent path of the star must be mapped. This could be achieved by centering the star before and/or after the occultation and then offsetting in the direction of motion of the comet--a procedure facilitated by the use of an orientable offset guider. The resulting profile should closely approximate the brightness contribution of the coma during the occultation

Whatever the procedure chosen, it will be necessary to standardize the photometry by observing a nearby comparison star from time to time. Depending on the observing conditions (variable transparency and sky brightness), offsetting to a comparison star should be done as seldom as possible (not at all near closest approach), and allowance should be made for the possible difficulty of recentering exactly on the star or cometary nucleus in some instances. Monitoring star brightnesses could also be accomplished by means of a two-star photometer, the use of a rocking secondary, or even observing simultaneously at a second nearby telescope.

One can envisage yet other observing techniques, such as repeatedly scanning the coma and star with a slit and modelling changes in the resulting image profiles, or observing simultaneously in the continuum and in an emission feature so as to distinguish between the effects of the true occultation and obscuration by clouds, etc.; but we cannot evaluate the efficacy of these methods without trial observations.

For occultations involving P/Halley in its upcoming apparition, conventional aperture photometry may offer some advantages:

- Fast response time will be useful--indeed imperative--for events that last just a few seconds.

- Because of the expected brevity of stellar extinctions, no photometric calibration should be necessary during an occultation.

- A small aperture can often be used, increasing the signal-to-noise ratio, provided the brightness distribution in the inner coma is properly measured and modelled.

- Since some relatively bright stars will be occulted centrally, moderate-size telescopes can be used. Thus it should be possible to deploy portable photometric systems in a coordinated effort to map the inner coma in detail.

Accurate Relative Astrometry

Larson and A'Hearn (1984), during the course of their CCD observations of a stellar occultation by C/Bowell, were able to determine the star-comet miss distance with an uncertainty of ±160 km, or ±0.09 arcsec, in the plane of the sky at the comet. From five observations, they were able to model the locus of the brightness peak of the diffuse coma (the nucleus was never isolated) as it moved past the target star. This result suggests that CCD imaging might provide a way to estimate the positions of comets relative to selected stars to an accuracy not greatly inferior to that of the best ground-based astrometry of solar system objects and certainly much better than that achievable for comets by conventional photographic means.

- The photometric integrity of CCD images makes them ideal for modelling the brightness distribution in cometary comae and, hence, in locating the point of peak brightness. The ready application of image-processing techniques enhances this property of CCD images. (The limited dynamic range of CCD images should be viewed as no more of a disadvantage than it is for photographic images; masking techniques can be used if necessary.)

- The large image scale, usually <0.5 arcsec/pixel, provides seeing-limited spatial information.

- The astrometric integrity of CCD chips at the few-thousandths-of-a-pixel level has been reported for stellar images by Monet and Dahn (1983). Experience with astrometry of asteroids and comets has convinced us and a number of our colleagues that the photocenters of sharp moving targets can generally be modelled to 0.2 pixel or better from single, good signal-to-noise-ratio images.

- The high quantum efficiency of CCD detectors implies that exposures on comets an order of magnitude shorter than photographic ones can be made. This is an important criterion, both for recording satisfactory images of the fastest-moving comets (~1 arcsec/sec) and of diffuse, low-surface-brightness comets.

Of course, even though high-accuracy astrometry should be achievable using CCDs, the positions are not absolute and can therefore only be as accurate as the stars'. To obtain accurate star positions on the FK4 (or, one hopes soon, FK5) system seems to necessitate a series of transit-circle observations of several years' duration (Harold E. Crull, personal communication), hence requiring the prediction of appulses further into the future than can usually be realized. Moreover, only rather bright stars would usually be considered. Thus, supposing that the positions of stars involved in cometary appulses are determined as carefully as possible by conventional astrometric means, one may anticipate that, in general, the accuracy of absolute cometary astrometry will be limited by current star catalogue zonal errors of 0.2 to 0.3 arcsec.

Appulse astrometry of P/Halley. We are planning to carry out accurate relative astrometry of P/Halley from Lowell Observatory. Our hope is that accurate observation of a number of stellar appulses will provide a series of "fiducial" astrometric positions of the comet that will allow significant orbit improvement as required by flyby missions. For the Giotto mission, for example, which arrives at P/Halley in mid-March 1986, the value of accurate astrometry increases steadily as the comet emerges from the dawn sky in the autumn of 1985 (R. Reinhard, personal communication).

Our calculations (Lumme and Bowell 1984b) and those of others (e.g., Hellmich and Keller 1981; Divine 1981) indicate that the nucleus of P/Halley should be isolable from its dust envelope, with good contrast, throughout the comet's apparition. According to Yeomans (1983), the nucleus should be brighter than B = 15 mag from mid-November 1985 until early May 1986. Thus, using a CCD camera attached to the 1.8-meter Perkins reflector, we anticipate recording images of

P/Halley's nucleus, together with those of nearby stars, in exposures of 2 sec or less during that interval. For each appulse, we will expose a number of frames, straddling the time of closest approach whenever possible. Because the exposures will be short, only P/Halley and the target star will normally be recorded, so it will not be possible to obtain a conventional multi-parameter "plate" solution. Instead, we plan to model the star-comet distance as a function of time, using the known apparent motion vector of the comet to establish the image scale and frame orientation. Bowell and Wasserman have identified a list of 151 stars that will be within 3 arcmin of P/Halley between 1985 August 13 and 1986 January 3 (solar elongation ≥50 degrees); interested readers may write for printouts. Taylor (1984b) has given a list of five wide appulses of P/Halley with bright stars during November 1985.

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REFERENCES

A'Hearn, M. F., and Millis, R. L. 1980. Abundance correlations among comets. Astronomical Journal. 85:1528-1537.

A'Hearn, M. F., and Millis, R. L. 1984. Comet 1983d: A conflict between the data from IRAS and data from the ground. Astrophysical Journal Letters, in press.

Allen, C. W. 1983. Astrophysical Quantities (London, England: The Athlone Press), pp. 243, 244.

Baum, W. A., Millis, R. L., and Kreidl, T. J. 1983. Narrowband CCD imaging observations of comets. Bulletin of the American Astronomical Society. 15:801.

Bowell, E., and Wasserman, L. H. 1984. Predictions of occultations of stars by P/Halley. International Halley Watch Newsletter No. 5, in press.

Combes, M., Lecacheux, J., Sicardy, B., Zeau, Y., Encrenaz, T., Vapillon, L., and Malaise, D. 1982. Occultations by comets. IAU Circular No. 3751.

Combes, M., Lecacheux, J., Encrenaz, T., Laques, P., and Sicardy, B. 1983. Stellar occultations by comets. In Asteroids, Comets, Meteors, eds. C.-I. Lagerkvist and H. Rickman (Uppsala, Sweden: Uppsala University), pp. 279-283.

de Pater, I., and Ip, W.-H. 1983. A radio source occultation experiment by Comet Austin (1982g). Bulletin of the American Astronomical Society. 15:805.

Divine, N. 1981. A simple radiation model of cometary dust for P/Halley. In The Comet Halley Dust and Gas Environment, pp. 47-53. ESA SP-174.

Dixon, R. S. 1970. A master list of radio sources. Astrophysical Journal Supplement. 20:1-503.

Dossin, F. 1962. Observation de la diminution d'éclat des étoiles vues à travers la région centrale de la comète Burnham (1959k). Inst. d'Astrophys. Univ. Liège Coll. 4, No. 120.

Dunham, E. W., and Goguen, J. 1983. Stellar occultations by comets. Bulletin of the American Astronomical Society. 15:804.

Hanner, M. S., Giese, R. H., Weiss, K., and Zerull, R. 1981. On the definition of albedo, and application to irregular particles. Astronomy and Astrophysics. 104:42-46.

Hellmich, R., and Keller, H. U. 1981. On the visibility of nuclei of dusty comets. Icarus. 47:325-332.

Landgraf, W. 1984. [osculating elements of P/Halley]. Minor Planet Circular No. 8665.

Larson, S. M., and A'Hearn, M. F. 1984. Comet Bowell (1980b); measurement of the optical thickness of the coma and particle albedo from a stellar occultation. Submitted.

Larson, S. M., and Sekanina, Z. 1984. Coma morphology and dust-emission pattern of Periodic Comet Halley. I. High resolution images taken at Mount Wilson in 1910. Astronomical Journal. 89:571-578.

Lumme, K., and Bowell, E. 1984a. Photometric properties of zodiacal light particles. Icarus, submitted.

Lumme, K., and Bowell, E. 1984b. Modelling the extinction of starlight by cometary grains. In preparation.

Marino, B., and Walker, S. 1984. Possible occultation of SAO 150943 by Comet Crommelin. Royal Astronomical Society of New Zealand Occultation Section Circular C84/6, pp. 1,2.

Meisel, D. D., and Morris, C. S. 1982. Comet head photometry: Past, present, and future. In Comets, ed. L. Wilkening (Tucson, Arizona: The University of Arizona Press) pp. 413-432.

Millis, R. L., and Elliot, J. L. 1979. Direct determination of asteroid diameters from occultation observations. In Asteroids, ed. T. Gehrels (Tucson, Arizona: The University of Arizona Press), pp. 98-118.

Millis, R. L., Franz, O. G., Wasserman, L. H., and Bowell, E. 1983. Occultations of stars by solar system objects. III. A photographic search for occultations of faint stars by selected asteroids. Astronomical Journal. 88:236-238.

Monet, D., and Dahn, C. 1983. CCD astrometry. I. Preliminary results from the KPNO 4-m/CCD parallax program. Astronomical Journal. 88:1489-1507.

Ney, E. P., and Merrill, K. M. 1976. Comet West and the scattering function of cometary dust. Science. 194:1051-1053.

Newburn, R. 1979. Physical models of Comet Halley based upon qualitative data from the 1910 apparition. In Proceedings, Comet Halley Micrometeoroid Hazard Workshop. ESA SP-153.

Nolthenius, R. 1983. Occultation by the nucleus of Comet 1983c. Occultation Newsletter. 3:86-87.

Taylor, G. E. 1984a. Occultations of stars by Comet Halley. Astronomy and Astrophysics. 135:181-182.

Taylor, G. E. 1984b. Occultations of stars by planets and comets 1985. IAU Commission 20 Working Group on Predictions of Occultations by Satellites and Minor Planets Bulletin No. 33.

Wallis, M. K. 1982. Dusty gas-dynamics in real comets. In Comets, ed. L. Wilkening (Tucson, Arizona: The University of Arizona Press), pp. 357-369.

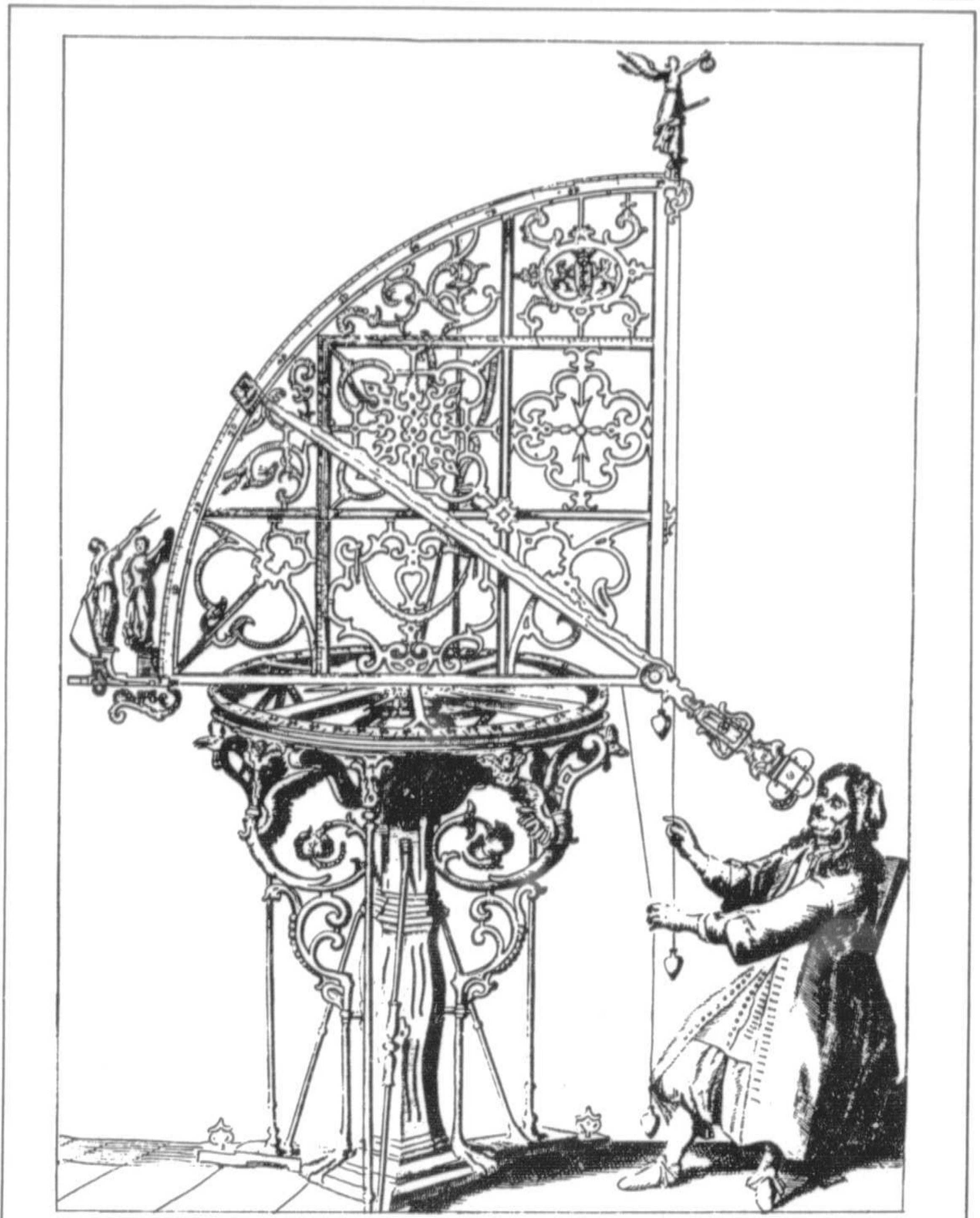
Wasserman, L. H., Bowell, E., and Millis, R. L. 1981. Occultations of stars by solar system objects. II. Occultations of catalog stars by asteroids in 1982 and 1983. Astronomical Journal. 86:1974-1979.

Wright, C. S., and Nelson, G. J. 1979. Comet plasma densities deduced from refraction of occulted radio sources. Icarus. 38:123-135.

Yeomans, D. K. 1983. [Ephemeris data for P/Halley 1982-1987]. Appendix B

in The Comet Halley Handbook, second edition (Pasadena, California: Jet Propulsion Laboratory, JPL 400-91, January 15, 1981), pp. 21-44.

Plate Reductions



Hevelius observing the sky with an azimuthal quadrant. From an engraving in Johannes Hevelius' 1673 work **Machinae Coelestis Pars Prior.**

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MEASURING -- THE QUANTIFYING ART

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ABSTRACT

The photograph of a comet or asteroid against background stars contains information in analog form regarding the relative positions of comet and star images. Measuring is the procedure for converting this information to digital form for computation of the object's accurate equatorial coordinates at the time of observation. This paper deals with the use of one- and two-coordinate measuring engines to measure the positions of images which may be elongated, comatic, or both, as well as round images, and the training of novice measurers to cope with such images. The grading of plates for potential accuracy of positions, preparation of plates for measuring, the accuracy of measurement, effects of telescope focal length and reduction technique upon the accuracy of positions, and the procedures and checks which may prevent erroneous positions also are discussed.

INTRODUCTION

In these tiny, sensitive chips of silicon which Drs. Belton and West have discussed, and I, too, have used, we see the shape of the future, as the dinosaurs might have seen the small, primitive mammals underfoot 200,000,000 years ago. But uniformly sensitive CCD's, without bad pixels or columns, still are hard to make, therefore rare and expensive; they require cooling with liquid nitrogen to be most effective; they require computers to control the acquisition of data and larger computers for the efficient analysis of the frames obtained. Most of us will be able to use them only as staff members or guest investigators at large observatories -- they won't be mounted on backyard telescopes in time for the Halley Watch. Furthermore, a comet image on a CCD frame is of no value to the orbit computer until accurate positions of faint stars on that frame are measured on photographic field plates which include enough reference stars from some well-defined catalogue so that the positions of the faint stars can be reduced to the system of that catalog. Only then, using those faint stars as secondary reference stars on the CCD frame, can the comet image be reduced to the same celestial coordinate system. Since field plates must be measured for CCD astrometry, since large photographic plates are better adapted than centimeter-size CCD's to searching for objects whose orbits are not as well determined or favorably placed as that of P/Halley, and since photography is better suited to the observation of brighter objects and their reference stars simultaneously, we astrometric dinosaurs with our measuring engines will still be alive and active after Halley has come and gone, and may still contribute to humanity's knowledge of the smaller bodies in the solar system, even at small observatories and with back-yard telescopes.

Many astronomers, even advanced amateurs, are acquainted with the observational techniques of photographic astrometry. In contrast, measuring techniques are not generally known. Aside from a useful paper (Eckert and Jones, 1962) and shorter sections (Konig, 1962; van de Kamp, 1962) in Astronomical Techniques, and Eichhorn (1974), they are rarely discussed in the astronomical literature. Most astronomers in the past have trained their students or assistants individually in the measuring techniques necessary to the course or project at hand.

With the development of semi-automatic measuring engines, and of scanning microdensitometers which can be programmed to function as measuring engines, many large measuring projects, including stellar parallax determinations and proper motion studies, are now carried out on such machines. The result is that fewer people have been trained in recent years to use the less sophisticated measuring equipment still to be found in many of the older and smaller observatories. Another recent trend is for groups of researchers whose astronomical training has not included even a plate measuring project in a Practical Astronomy course to engage in solar system astrometry, to delegate one of the group to measure the resulting plates, but to provide that person with little or no instruction in measuring techniques. Since some who might wish to participate in IHW astrometry may find themselves similarly lacking in experience or training at the measuring engine, it seems advisable to present the full-length paper from which was edited the shorter version read at the International Halley Watch Astrometry Net Workshop (Munich, 1984), so that more details of measuring practices and the reason for those practices might be discussed. Some questions raised after that paper was read involved information which could not be included in a 10-minute oral report (which ran overtime, even so!), but which appeared in this paper from the earliest drafts.

RECOMMENDED PROCEDURES: OBSERVATION AND REDUCTION

Measurement and reduction are the intermediate steps between the exposed photographic emulsion (on film or glass plate) and the accurate position reported to the International Halley Watch. The procedures of measurement and the accuracy of the resulting position will be affected by the observation which precedes the measurement, by the reduction which follows the measurement, and by the measuring engine upon which the measurement is carried out.

The most accurate positions will be obtained from well-exposed, well-guided emulsions exposed with telescopes of adequate focal length. Astrometric exposures for a comet should be just long enough to produce a measurable image of the nucleus, and not so long that the coma builds up sufficient density to obscure the true position of the nucleus. Exposures for tail structure will be far too long for accurate astrometry! The shorter the exposure, the shorter the star trails, and the more accurately they can be measured. On a well-guided exposure, star trails will be linear and uniform in width, the nucleus image will be round, if guided at the rate of motion of the comet; or star images will be round and the trail of the nucleus will be straight, if guided at sidereal rate.

As for focal length, there is a rule of thumb that on the emulsion, 1 arc second equals 5 micro-meters times focal length in meters ($1'' \approx 5\ \mu\text{m} \times \text{f.l.}$). Since, as discussed below, the probable error of a star image measure is about ± 3 μm, a telescope with focal length 0.6 m might produce the desired 1-arc-sec accuracy about half of the time, but at the cost of painstaking effort at the measuring engine. If there is a choice of instruments, better positions will be obtained with less effort from plates exposed in telescopes of 2 meter or greater focal length. Longer focal lengths and larger plate scales may also make possible the resolution of the nucleus within a bright, diffuse coma, and increase the latitude of exposure within which such resolution might be possible.

The reduction technique to be used determines how the plate should be oriented for measurement. If the star trails are appreciably elongated, the measures will be most accurate if the trails are aligned parallel to the horizontal or the vertical cross-hair in the eyepiece. Some reductions lose accuracy if the plate is not accurately oriented with the N-S and E-W directions at the plate center parallel to the motions of the carriages, regardless of the orientations of the star trails, or if the program object is not at the centroid of the reference star array. The Least Squares Turner Six-Constant Method, or Turner Reduction, permits the object to be anywhere within the reference star array and the plate to be oriented at any angle necessary for maximum measuring accuracy. Experience has shown that the Turner Reduction will produce usable positions even when the plate is rotated by nearly 45° from a N-S, E-W position, or when the reference stars are all on one side of the center star (which also is a reference star) and the comet is on the other side, at about the same distance from the center star as is the centroid of the reference star array.

The Turner Reduction is the reduction recommended for International Halley Watch astrometry; the rest of this paper assumes that the Turner Reduction is used. For the sake of computational accuracy and speed of reporting, this reduction should be programmed for a small computer in advance of Halley Watch, and the program checked out to see that it does what it is intended to do. It has been programmed in Fortran and Basic (though some desirable features are omitted) and will even fit into the Hewlett-Packard 41CV with up to 10 reference stars, with program memory space left over.

THE MEASURING ENGINE: DESCRIPTION

A measuring engine is a device for determining with utmost accuracy the relative positions of a number of images in two coordinates, called "X" and "Y", with axes at 90° to each other, similar to positions on a piece of graph paper, except that the zero point in each coordinate may be somewhere outside the area of the plate, rather than in the center of it. Mechanically, the measuring engine consists of two carriages sliding on accurately-machined ways which constrain the carriages to move in straight lines at 90° to each other, but in parallel planes. The upper carriage carries a microscope with cross-hairs in its eyepiece, or other image-locating device, and moves from side to side in front of the measurer. The plate is mounted on the lower carriage and moves toward or away from the measurer. The range of motion in each coordinate is sufficient to bring the microscope to bear upon any point on the largest plate that is to be measured. Once the microscope is focused upon any point on the plate, any other point will be in focus as well if the plate is mounted parallel to the ways on which its carriage moves and if the carriages move in accurately parallel planes. (This fails only if the plate is on thin glass and is large enough to sag appreciably between its supports, for example, the 14x14-inch plates on 1-mm glass used in the 1.22-meter Schmidt telescopes.)

The stage of the measuring engine, to which the plate is attached, is usually a turntable mounted on the plate carriage. The stage may be rotated through 360° so the plate may be set at any desired angle to the ways on which the plate and microscope carriages move, or to the cross-hairs in the eyepiece. Both plate carriage and turntable are open through the middle, so the plate can be illuminated from below by transmitted light, the "field illumination". The rim of the turntable may be graduated from 0° through 359° and equipped with a vernier scale so that its position can be read to 0°01 or less, depending upon the size of the turntable and the scale of the divisions in its circumference.

On older measuring engines a high-precision screw turns in a nut attached to the microscope carriage to move the carriage and to sense the position of the carriage. The position is read out from a pointer on the carriage and a scale on the frame of the measuring engine, or by a rotation counter geared to the screw, in turns of the screw. A drum, attached directly to the screw, graduated to 0.001 turn, shows the fraction of a turn up-scale from the last division. If the screw advances the carriage by 1 mm per turn (as is usually the case), then the drum will read out in units of 1 micron (μm). Many of these engines are tilted up from the horizontal by 30° to 60° or more, have the plate carriage counterbalanced by weights hung from cords or light cables running over pulleys attached to the top of the base frame of the engine, and have only a millimeter scale and a pointer to indicate roughly the position of the plate up or down the scale. These are single-screw or "X engines" and measure only one coordinate accurately at a time. In order to measure the other coordinate, Y, the plate on its turntable must be rotated through exactly 90°, using the rotation scale on the rim of the turntable.

More efficient engines have the plate carriage and its ways horizontal, so that the plate carriage, like the microscope carriage, can be driven and sensed by a high precision screw equipped for position determination. Then an image can be measured in both coordinates, X and Y, at the same time, once the plate and microscope have been moved so that the desired image appears in the field of the microscope. These are two-screw, two-coordinate, or "X-Y" engines. Measuring techniques differ slightly between X and X-Y engines, but only in detail. Both most commonly have numerical scales so arranged that X will increase as the microscope moves to the left and Y will increase as the plate carriage is moved downward or toward the measurer (microscope moving upward with respect to the plate), whether Y is measured or only indicated.

Both will have handwheels for moving the carriages so that the desired image appears in the field of the microscope eyepiece for setting. On an X engine, the Y motion will be driven by a rack and pinion. For the X motion, and both motions of the X-Y engine, the handwheels attach directly to the ends of the measuring screws, adjacent to the drums which show the fractional turns of the setting. These drums are accurately graduated scales. Measurers should take care to keep fingers or hands off those scales, lest dirt or skin acids damage the surfaces or graduations. Even if there are shaft encoders on the other ends of the screws, and settings are routinely read into a computer terminal or other display system, the drums should be protected from damage. Electronic equipment will occasionally fail, most probably when an important plate is to be measured. Then legible drums will be the difference between publishing a position and coming up empty-handed.

Both X and X-Y engines have pre-loads on the carriages with which the measuring is done. Pre-loads are weights attached to the measuring carriages by cords which run over pulleys attached to the frame of the engine, so the effect of the hanging weight is to pull each measuring carriage back toward the direction of decreasing scale reading. The motion of the measuring carriage in making the bisection of an image for the record must always be the direction which causes the weight to be pulled upward. This will ensure that the carriage is always being set and its position read against the same side of the screw thread, and that the screw itself is seated firmly in contact with the thrust bearing at the same end of the screw. Thus, the effects of any looseness of the carriage nut on the screw threads, or of the screw in the bearings where it is supported by the frame of the measuring engine, are minimized, and as far as possible, the same from image to image.

Accuracy

The accuracy of a measuring engine depends upon the accuracy of the measuring screws and of the ways on which the carriages move. With careful cutting and lapping, testing, and, if necessary, mechanical correction of the screws, errors arising from the screws should be 1 μm or less. If the measuring screw is mild steel and the nut is bronze, the screw should retain its accuracy for many years, as any wear which may occur will take place on the softer metal of the nut, rather than the screw. Similarly, precision machining and testing procedures should produce ways which will be straight over their length within ± 1 μm or less, so that the intrinsic accuracy of the measuring engine should be ± 1 or 2 μm if it has been treated with the care which accurate mechanism deserves.

A measuring engine which has lain idle for a long period of time should be cleaned to remove old oil, gum, and dirt from screws and ways, and carefully re-lubricated before being used. If there is any trace of rust on screws or ways, the engine must be checked carefully for accuracy before being used for critical work -- it may no longer be good enough, or may need reconditioning by an instrument maker with experience in measuring engine maintenance and repair.

When a measurer makes several attempts to bisect a moderately large star image, they will probably fall within ±2 or 3 μm of a mean value. Combining this with the errors which may arise from the engine itself, the probable error of a good reference star measure should be ± 3 μm, more or less. For small images, the accuracy of measures is comparable to the accuracy of the measuring engine.

This simple-minded treatment of accuracy considers the errors of screws and ways to be random. Actually, they are systematic, depending upon the position of the carriage on the ways and the nut on the screw. If there is reason to suspect the accuracy of ways or screws, there are techniques for checking their accuracy and determining corrections which can be added to the raw measures as part of the reduction, if the corrections are found to be significant (Eckert and Jones, 1962; Eichhorn, 1953).

Oil Film Effects

One source of error may vary from point to point on the screws and even from setting to setting at the same point of the screw: the thickness of the oil film between the screw threads and the nut. If the screws have just been cleaned and re-lubricated, the oil may not have distributed itself uniformly along the screw, or too much oil may have been applied to begin with. Suspect the latter if the screw turns very easily, and the carriage seems to float along the ways. Where that happens, find a small image, dust speck, or plate defect, and set it on the cross-hair for measuring in that coordinate. Note the setting. Apply pressure by one finger to the up-scale end of the carriage, just above the screw, in line with but opposing the motion of the carriage to set the image for measurement. Maintain the pressure as the screw is turned to move the carriage back and forth past the image until a resistence is felt by the hand turning the screw. Then back the carriage so the image is two turns away from the cross-hair, start the image toward the cross-hair, release the pressure, and bisect the image again. Note this setting, also. The difference between this and the previous setting is the effect of the oil film at that part of the screw. This effect has been measured at 40 μm or more, a difference of nearly 3" on the scale of the 1.22-m Schmidt telescopes, or 9" on films from the 0.46-m Schmidt at Palomar.

If significant oil film effects are found, this procedure for reducing the oil to a standard thickness may be necessary for every image that is to be measured. Take care not to force too much of the oil out of the way, lest the screw or nut be subjected to excessive wear, and to loss of accuracy in the long run. When measuring an image, finger pressure should be reapplied to the carriage after the setting is recorded. Advance the carriage a fraction of a turn beyond the setting, then back off by two turns and start to advance on the next setting before releasing pressure for the last few hundred μm of travel to the next setting. The carriage must have some distance in which to smooth out any misalignment which may result from the pressure on the carriage. If an X-Y engine is used, it may be necessary to control oil films on both carriages in this manner. Even if oil film problems are not obvious, it may be prudent to run the carriage(s) slightly beyond the setting point before and after each setting in order to prevent oil from building up on the screw at the setting point. However, the carriages should always be allowed to run freely, without pressure, when slewed from one image to the next.

MEASURING: SOME FUNDAMENTAL CONCEPTS

Measuring is the art of estimating by eye where the center of an image is, then of setting that image on the cross-hairs so that either the vertical hair lies on that center or the intersection of the cross-hairs coincides with that center. To look at it from a less intuitive viewpoint: when an image, round or trailed, of a reference star, comet or minor planet is seen through the measuring engine microscope, one may visualize the horizontal and vertical cross-hairs in the eyepiece as knife edges upon which one will try to balance the image, successively and independently of each other. As the image is moved across each of the cross-hairs, there will be many positions where the image would not balance, and one position of the image where it would balance. In that position, the cross-hair passes through the centroid or "center of gravity" or "center of light" of the image. This is the position which should be recorded for the image in that coordinate. Two such balance lines (in X and Y, in this case) define the centroid of the image, in a manner strictly analogous to defining the centroid of a two-dimensional physical object. Estimating the center of a round image is not difficult, if the image is not too large or small. If the image is elongated by several times its width, estimating the centroid is more difficult at best, but as easy as is possible if the long dimension of the trail is parallel to one cross-hair or the other.

Moving-object astrometry depends upon the assumptions that we can measure the position of the center of light for any image, round or elongated, and that the measured centers of a long star trail and a round comet nucleus image correspond to the same time of observation, the midpoint of the exposure. The latter assumption is essentially true if the star trails are straight, uniform in width, and uniform in density. If star trails taper due to atmospheric extinction, or start to taper near the end of an exposure because clouds are increasing, this assumption fails, and positions will be less accurate as the time corresponding to the centroid of the star trails differs by some unknown amount from the time of mid-exposure. Similarly, if star trails curve due to flexure in the telescope-guider system, or appear as strings of dots because the device to offset the motion of the comet repeatedly sticks and jumps or if the wrong rates of motion are set into that device, the comet image will be elongated. It may be more difficult to measure the centroids of star and comet images accurately in these cases, so the accuracy of the resulting positions may be diminished. If the comet image should be pear-shaped, or varying in density along its length, as a result of these instrument problems, it cannot be measured to give a position accurate enough to be useful for IHW.

A measure is defined as the mean of three attempts to bisect the image as described above, with a fourth bisection in dubious cases. For any such group of settings, a mean can be formed, and the differences of individual settings from that mean can be computed. These differences can be combined into a root-mean-square error, a measure of the reliability of the measure. This implies that the accuracy of the resulting measure will increase as the square root of the number of settings made. If we make three settings and want to double the accuracy of the result, we would have to take the mean of twelve settings to achieve that improvement. Beyond three or four settings, one additional setting included in the mean does not increase the accuracy of the result enough to justify the labor of the setting. Therefore, three settings are sufficient for our purposes.

PREPARATION OF PLATES OR FILMS FOR MEASUREMENT

The exposed emulsion (on glass or film) is developed, fixed, washed, treated with Photo-Flo, and left in a gentle flow of dust-free air in a plate dryer until it is completely dry (Miller, 1979). A plate may immediately be set in a scanning frame or on a light table for examination, with the glass side up, supported so that the emulsion does not contact any surface or object except at the edges, where the plate holder supported it in the telescope. Films may be sandwiched between pieces of clean glass to hold them flat for examination.

Evaluation of Images

Plates or films may be examined with a magnifier of 10x or higher power. From the shape of the star trails (straight or curved, tapered or uniform in width) and the character of the comet image (round, elongated, trailed, diffuse with condensation, diffuse without condensation) it is possible to make a preliminary objective estimate of the potential accuracy of the resulting position, as described in Table 1. One can easily see. even at 10x magnification, which exposures will be worth measuring and which should be rejected.

Table 1. Evaluation of Plates for Potential Accuracy of Position.

Images	Position
Star trails straight, uniform width; comet nucleus small, round or slightly elongated, or well-defined condensation in weak coma	accurate
Star trails straight, of uniform width; comet small or with condensation, but outside reference star array or near edge of plate; or comet diffuse, without central condensation	less accurate
Star trails slightly curved, of uniform width; comet slightly trailed, of uniform width and density	less accurate
Star trails straight, but slightly tapered; comet round or slightly elongated	less accurate
Star trails more severely curved, but smooth arcs; comet image trailed, but uniform in width and density	semi-accurate
Star trails more severely tapered; comet image round	semi-accurate
Star trails straight but ending at unknown time due to clouds; comet image round	semi-accurate to rough
trails curved and tapered, or irregularly curved, angular or broken; comet image irregular	rough

Accurate positions are reported to $0\overset{s}{.}01$ in right ascension (R.A.) and $0\overset{\prime\prime}{.}1$ in declination (Dec.) and are probably accurate to a few tenths of an arc second in each coordinate. Less accurate positions are also reported to $0\overset{s}{.}01$ and $0\overset{\prime\prime}{.}1$, but may be accurate in the range of several tenths of an arc second to an arc second or more in each coordinate. They are reported and published with the qualifications cited (comet near edge of plate, comet diffuse, star trails curved, or others, as applicable), to explain why the measurement may be less accurate or why there may be systematic error between the measured center of the star trail (or the time corresponding to it) and the measured position of the comet.

Semi-accurate positions are reported to only $0\overset{s}{.}1$ and 1", respectively, and may be accurate to a few arc seconds. Semi-accurate positions will be useless for orbit improvements for Halley and should not be reported. They are useful for other objects only if they prove to be the only observations of that object in that season, or if they should point the way to other, more accurate observations in the same apparition of the object. Exposures which might provide rough positions are useful only as a guide to do better the next night! At least, you know the object is there!

Identification of Reference Stars

Once a film has been accepted for measurement, it should be laid, emulsion-side up, in the middle of a clean piece of glass large enough so that it will not fall through the open center of the measuring engine stage. A similar piece of glass should be laid on top of the film, over the emulsion side of the film. This glass-and-film sandwich should be taped together tightly enough so that the film does not slide around between the glasses, and marked so that one knows which is the emulsion side of the film. Then it, like the plate, is ready for reference star identification.

If the exposure has no indication of orientation, mark the north (N) and east (E) edges of the glass to indicate those directions as determined from the Smithsonian Astrophysical Observatory (SAO) star charts or similar charts. Identify catalog stars by marking on the glass with a fine-tipped felt pen. It may be helpful to plot the catalog stars on graph paper in advance, if no charts of the star fields exist, or images may be identified differentially from a known star, numbered on the glass, and the reference star array selected from the catalog stars. Reference stars should not be overlapped by other stars unless no alternative reference star is possible. Each image should be marked with some identification so that you can tell which catalog star it represents. Usually, the last two digits of the current number of the star in the catalog is an adequate identification on the glass.

Star field identification is particularly easy if the telescope has been guided by a parallel guide telescope. Then the center star is known, and other stars can be identified differentially from it by use of a millimeter scale. Also, the guide star image can be measured, and its position used as the plate center for the reduction.

In the classic curved-field Schmidt, any star which is near the program object and not too close to the edge of the plate may be taken as the center star for a reference star array in a local reduction which will adequately represent the reference star positions within a radius of 1° to $1\overset{\circ}{.}5$ or so around the center.

If such local reductions are contemplated, the reduction program should provide for the designation of that star as the plate center and the subtraction of its measured coordinates from those of all other images, including the comet, so that it becomes the center for the reduction, as well. Otherwise, if the plate must be rotated from a N-S, E-W orientation, the large numbers coming in from the center correction terms (c and f in the Turner Reduction) may threaten the accuracy of the solutions, if more than a minimal number of stars are used in the reduction.

While the Turner Reduction will yield meaningful results with as few as four reference stars, it is better to use six to eight for a small plate or a local reduction of a large plate. No star catalog is perfectly accurate or even totally consistent. (Eichhorn, 1974.) The more reference stars used, within reasonable limits, the less effect one poor reference star position or proper motion will have on the accuracy of the resulting comet position. One poor reference star may be detected more readily, the more reference stars there are, and rejecting that star, if necessary, will still leave enough stars for a strong determination of the plate constants. If the reduction has been programmed for a small computer, then the only extra time required for more than the minimum number of reference stars is the time involved in selecting them and measuring a few more images.

When the reference stars have been selected, it may be helpful to orient the plate on the scanning frame as described below, note on paper the reference star numbers as given in the catalog in order from westerly to easterly edges of the plate, and also to draw lines on the glass from near each star or comet image to near the next image to be measured. These lines will save time in going from star to star when measuring. The notation of the catalog numbers of the reference stars will guide the measurer in writing out a list of catalog positions and proper motions for use in the reduction.

In all these manipulations of plates and films, the utmost care should be taken not to get fingerprints or other marks on the emulsion or, in the case of film, on any part of the film or the interior surfaces of the glass sandwich. Films may best be handled by the edges, using tweezers. Tweezers should also be used to move films into and out of glassine storage envelopes. Plates should be handled as much as possible by the edges, with the thumb and fingers spanning the plate so that only the edge of the glass is handled. Larger plates should, similarly, be supported by the edges between two hands, when handled. When sliding plates into or out of storage envelopes, always compress the envelope from edge to edge so that the plate may still move easily into or out of the envelope, but the paper of the envelope is sprung out so that it does not come in contact with the emulsion while the plate is moving into or out of the envelope.

THE MEASURING ENGINE IN USE

Preliminary Adjustments

Before mounting a plate on the measuring engine, one should turn on the field illumination and be sure that the cross-hairs are at the infinity focus of the measurer's eye, whichever eye -- right or left -- is normally used at the microscope eyepiece. If that eye has uncorrected astigmatism, rare in these days of contact lenses, the focus for an X-Y engine will be the best compromise between a sharp horizontal cross-hair and a sharp vertical cross-hair. For an X engine, the vertical hair should be sharply in focus. As in all microscope work, the other eye should remain open throughout. It may be shielded from distraction from field illumination by an opaque black screen hung from the microscope carriage, or by a piece of black cardboard with a hole in its middle to hold it onto the microscope tube in front of the eyepiece. One can also wear a black eyepatch, as long as the eye can be open under the patch.

Some measuring engines are equipped to project the images of the stars or comet from the plate onto a screen for measurement, rather than to the measurer's eye at the eyepiece. Projection-type engines have the advantages that the measurer can wear ordinary eyeglasses and correct all visual problems at once, and can measure with both eyes. A disadvantage is the intensity of light required to project that image to the screen, and the accompanying heat input to the measuring engine, to the plate on it, and to the measuring room at large. Because of this heating, when using a projection-type engine one always measures the comet image before all of the reference star images and again, after all the reference star images have been measured in this orientation of the plate. The numbers that go into the reduction in order to solve for the position of the comet will then be the means of the measures before and after the reference stars. However, if the difference between the first and last settings on the comet image in either coordinate is greater than the number of microns corresponding to 1 arc second, the whole set of measures should be rejected and the plate remeasured, after steps have been taken to get rid of excess heat in the measuring room, so that the temperature will stay more nearly constant.

Orientation

The measurer should also check that the cross-hair is parallel to the motion of the plate carriage and adjust it, if necessary. Find a small image, a dust speck or plate defect; bring it to one end of the vertical cross-hair (End 1) and adjust the microscope carriage so that the vertical cross-hair bisects that image. Then, move the plate carriage so that the image travels to the level of the other end of the vertical cross-hair (End 2). If the vertical cross-hair still bisects the image at End 2, the adjustment is good. If the vertical cross-hair does not bisect the image at End 2, rotate the cross-hairs so that End 2 travels half-way from its original position to the image. Return the image to End 1. Bisect it again with the vertical cross-hair; then return the image to End 2 again. If it is not exactly bisected, again rotate the cross-hairs so that End 2 travels half-way from this position to the image. Return to End 1, bisect again, and continue this cycle until the image is bisected at both End 1 and End 2 without further adjustment in either the cross-hairs or microscope carriage. This is an example of a procedure which is performed any time it is necessary to bring the long dimension of an image or the edge of a plate or a cross-hair parallel to some line inherent in the measuring engine.

Once such an orientation operation has been completed, the rotating structure which has been oriented should be clamped or taped into position so that it will not accidently be moved from that orientation.

Mounting and Orientation of the Plate

Once the eyepiece has been focused on the cross-hairs and the cross-hairs have been aligned, the plate (or film sandwich) to be measured is clamped, taped, or otherwise firmly attached to the stage of the measuring engine, so that it cannot slide or rotate on the stage. The emulsion side of the plate or film should be up. The east end of the plate should be in the direction of increasing scale values in X (usually to the measurer's left). For a normal refractor or un-folded reflector, North will be up, in the direction of increasing scale values in Y. The Turner Reduction requires this orientation, plus or minus 45°, for maximum reduction accuracy.

If the reduction program allows for an offset center (local reduction of Schmidt plate), the center of the plate need not be exactly in the center of the plate carriage. If the plate is small and the measuring engine used will accommodate large plates, it is better to mount the small plate off the center of the carriage. This will spread the wear over more of the screw, rather than concentrating all the wear from small-plate measuring in the center of the measuring screw(s).

If the plate is a short exposure taken with the telescope operating at sidereal rate, reference star images will be round and the image of the comet will be round or only slightly elongated. Such plates may be oriented by making the long edge of the plate parallel to the motion of the microscope carriage or the plate carriage, whichever gives the closer approximation to a N-S, E-W orientation as described above. This is accomplished by the same sort of iterative translation and rotation process described for the eyepiece, except that we are using the long edge of the plate as close as possible to the corners of the plate as the object which is to be made parallel to the ways. It may be necessary to illuminate the edge of the plate where it rests on the turntable so that it can be seen in the eyepiece, and so that this orientation procedure can be carried out. It may also be necessary to focus the microscope on the edge of the plate in order to carry out this procedure.

If the plate is a long exposure with the telescope guided for the motion of the comet, the comet image will be round and the star images will be elongated trails. The trails can be measured most accurately if they are aligned with their long dimensions parallel to one cross-hair or the other, whichever orientation is closer to the N-S, E-W position referred to above. This orientation should be carried out using a star near the center of the plate or the reference star array, in case differential refraction causes trails near the edges of the plate to diverge or converge slightly.

Otherwise, the orientation process is as previously described. If the star trails are straight or slightly curved, the final orientation should be such that one cross-hair passes through the centers of both ends of the trail.

Once these orientations have been accomplished by appropriate rotations of the turntable, the position of the turntable should be recorded as precisely as possible, using the graduations on the rim of the turntable and the vernier scale, if any. This is particularly necessary when using an X engine, because the next coordinate to be measured after X will require a rotation of the turntable by exactly 90°. The turntable adjustment should not be touched until it is necessary to set it for the next coordinate.

Some measuring engines are designed so that the plate and microscope carriages can be unclamped from the nuts by which they are driven, and moved at will in either direction on their ways. This makes it easier and faster to perform the foregoing alignment procedures. Of course, before measuring, the carriages must be reconnected to the nuts and checked to make sure that they are properly clamped to the nuts. You can be sure that you're ready to measure if you cannot push or pull the carriage either way along its ways by hand.

Focus for Measuring

Now that the plate is oriented for measurement, the entire microscope should be focused. Move the microscope and plate carriages so that the image of the comet is bisected by the vertical cross-hair and lies just above or below the horizontal cross-hair in the eyepiece. Move the microscope in or out until this image is in focus. To check the focus, move the eye a short distance back and forth across the field of the eyepiece (if you're losing sight of the image at the ends of the motion, you're going too far!). Note whether the cross-hairs appear to move from side to side over the grain of the plate. If they do, adjust the focus until there is no apparent relative motion. This is "focusing by parallax". When the focus has been set, it should not be changed during the measurement of a plate in this orientation, lest the focus adjustment change the angle of the microscope with respect to its carriage, and introduce a systematic error in all subsequent measures. If some image at one edge of the plate is out of focus, the measurer must try to align his eyeball with the eyepiece just as for all the other images, and do the best he can to bisect the image.

Auxiliary Field Illumination

In the orientation or the focusing process, we may find that the plate background is so dense that images are seen only with difficulty, or that the cross-hairs cannot be seen at all over the images of the reference stars. If this occurs, auxiliary illumination is required under the stage. This can take the form of a long tubular incandescent display case lamp, if the space under the stage is large enough to accommodate it. It is most effective if it lies directly below the microscope objective, with its long dimension parallel to the motion of the microscope carriage. When auxiliary illumination is used, the comet position should be measured before and again after all of the reference stars have been measured in this orientation. As with the projection-type measuring engine, if the difference between first and last measures is greater than 1 arc second equivalent in microns, the measures should be rejected, and this coordinate remeasured. If the measures are accepted, the numbers that go into the reduction in order to solve for the position of the comet will then be the means of the measures before and after the reference stars in each coordinate.

MEASURING THE PLATE

When these preliminary adjustments have been completed, the plate is ready to be measured. Measurers should keep in mind certain guidelines on measuring techniques and procedures (see Table 2). Most of these refer to measuring with a screw-position read-out and manual recording; the last two are more specifically directed to users of engines with linear encoders and automatic recording of settings.

The intent of the first two guidelines is that backlash be controlled as discussed in THE MEASURING ENGINE: DESCRIPTION, above. No. 3 is intended to prevent oil build-up on the screw at the point of setting on the image, as discussed in <u>Oil Film Effects</u>, above, if more radical oil film control measures are not required.

Plate measuring is widely considered to be a boring occupation. It is guaranteed to be boring if the measurer spends all day on a plate with only six reference stars and one comet image, sweating over the eyepiece in an effort to bisect each image to the last half micron. The next six guidelines are recalled from a training session with Dr. S. Vasilevskis, now Astronomer Emeritus at Lick Observatory, whose astrometric studies of galactic cluster membership required the measurement of large numbers of star positions with high accuracy. These instructions have the aims of:

1. developing speed in measuring, so the job doesn't take all day;

2. developing a consistent pattern of systematic errors in setting on images of different sizes, so that if the measurer tends to overshoot the center of bright star images, compared to faint star images, he will at least overshoot images of the same size by the same amount, wherever he encounters them on a given plate. By the time a plate is completely measured, provision will be made for the elimination of such systematic errors.

3. avoiding any sort of bias of one setting on an image by any other setting, good or bad, which may have been made on that same image.

These guidelines were developed for the measurement of the round images produced by a long-focus refractor, using an X engine. They

Table 2. Some Guidelines for Measurers.

1. ALWAYS bring image to cross-hairs in the same direction -- its apparent direction of motion when the carriage moves toward increasing scale values.
2. NEVER back up to correct the centering. If you overshoot, see 3.
3. ALWAYS, after making a setting, advance the image beyond the cross-hairs by a fraction of a turn, then back off by two turns and approach the cross-hairs for the next setting. Advance the image similarly and back off before making the first setting, as well.
4. ALWAYS set smoothly, without stops and starts.
5. ALWAYS estimate the center of the image as it approaches the cross-hair and try to stop the image with the center on the cross-hair.
6. NEVER adjust a setting. If centering looks good, record the setting; if centering seems unsatisfactory, reject it and reset.
7. NEVER look back -- at image, once the setting has been recorded or rejected; -- at read-out, if setting has been rejected.
8. NEVER stop and agonize over a bisection. Retinal fatigue will soon make even the best bisection seem doubtful.
9. NEVER estimate corrections or apply them in recording -- never say, "It's 3 microns too high; I'll take 3 microns off the reading"!
10. NEVER look at records of previous settings on an image, lest you subconsciously try to duplicate them.
11. ALWAYS remove hands from handwheels after making a setting, lest the muscles and nerves "remember" their position for the setting.

apply in detail any time when round images are being measured, but all measuring should be guided by the intent of these guidelines.

The last two guidelines, suggested by Dr. R. M. West in the discussion following this paper at the Astrometry Net Workshop share the third aim of avoiding the influence of one setting by another, but apply to engines where the measurer need not back off two turns of the screw between settings on the same image or take his hands off the handwheels to record numbers.

We define a setting on an X engine or an X-Y engine as a satisfactory bisection of the image in one or both coordinates, respectively. A measure of an image is the mean of three such settings, each of which should be recorded as it is made, then not looked at again until the last setting has been completed. All digits should be recorded each time, not just the decimals in the last two settings. There is always the possibility that digits may be transposed in the recording of a five or six digit number, or that the wrong integer may be read from a scale when the fraction is just above or just below 0.000. (For example, after recording a measure of 123.998, it can happen that the next setting ends in .002. Utilizing only the decimals in recording will give the impression that the two measures are nearly a millimeter apart! Recording the setting as 124.002 clarifies the reading immediately.)

Before averaging the three settings, inspect the numbers recorded. If two numbers agree within a few μm and another is several μm away from them, a fourth setting may be made. If this setting yields a value near the single number or between it and the other two, average all four settings; if it agrees with the two close values, discard the discordant value and average the other three. If the first setting gives a smaller value than the other two (or three), it is possible that the thickness of the oil film on the measuring screw may have decreased between the first and the later settings; if the settings produce continually increasing numbers, the oil film may still be decreasing. In the worst case, none of these settings may mean anything. (See Oil Film Effects, above).

After measuring the comet image for the first time, one simply measures his way across the plate from West to East, going up or down as necessary to reach the next image, and returning to measure the comet again after measuring all the reference stars. The listing of the reference stars in order from West to East, with the plate in the orientation in which it will be measured was, in part, a plan for this procedure (See Identification of Reference Stars, above).

If some of the reference stars are bright enough to show diffraction spikes, these may be useful as an indication of exactly where the center of the star image or trail really is. Some telescopes, in particular the Schmidts, will have images which are expanded in one direction or another by aberrations, so that the center of the roughly circular image does not coincide with the center derived from the diffraction spikes. Measures based upon the diffraction spikes appear to be more consistent with positions of fainter stars than do measures of the center of the seeing disc of a bright star. However, one should look quite carefully at the diffraction spike pattern before measuring on it. Some telescopes may have other diffraction or reflection effects which will distort the spikes so that they are not a true indication of the position that the star would occupy if the exposure were short.

Setting practices may differ slightly between X engines and X-Y engines. In working with an X engine, the measurer may find it less distracting to avoid the intersection of the cross-hairs, and to measure everything completely above or below the horizontal cross-hair. When measuring the comet image, it should be bisected by the vertical cross-hair at about the same distance from the horizontal cross-hair as the centers of the star trails were measured. Because it is easier to bisect an image in one direction than in two, it may be better for the beginning measurer to start with an X engine or to treat an X-Y engine as an X engine for the first few plates.

Settings with an X-Y engine are slightly more complex, especially with elongated or trailed star images. Ideally, one should evaluate the point about which the image would balance as the image approaches the cross-hairs, bring that point to the intersection of the cross-hairs smoothly and simultaneously in both coordinates, stop with that point on the intersection, and record both coordinate values. The beginner should try this on a practice plate or two, and see how the results come out. If this approach does not go well, alternatively one may bisect the images in one coordinate, then in the other. The measurer's feeling for what is comfortable to his eye, brain, and hand will determine whether the long dimension of the image or the short dimension is bisected first. If the first dimension appears clearly under-set when the second has been bisected, one quick adjustment of the first dimension may be permitted; in the event of an overshoot in either dimension, both screws should be backed off and the image bisected anew in both coordinates. The object still is to move reasonably rapidly from setting to setting and to invest little enough time in any individual bisection so that it doesn't hurt to reject it and reset. This is not to say, however, that the carriages should be moved rapidly as one approaches the estimated center of the image. The setting motion should be smooth, slow enough so that the carriages may be stopped smoothly at the estimated center of the image, so that the inertia of the carriage does not overcome the friction of the lubricated ways to cause an apparent overshoot.

If we are working on an X engine, all that has been recorded is a set of measures in X; Y measures are also needed. To measure Y, the turntable of the measuring engine must be rotated by exactly 90° in the direction such that one arrives at an orientation with the northerly portion of the plate lying in the direction of increasing X. The procedure of measuring the comet, reference stars, and comet again is repeated; this time, the measures are labeled "Y".

If the plate is measured on an X-Y machine, the result of the measuring will be a list of star numbers with recorded settings in two coordinates, which we label, provisionally, "X" and "Y".

When the measures are reduced, we must know with utmost accuracy the position of each reference star and the comet with respect to the center of the plate or the center star of the reference star array, which also has a known position in the sky. The simplest way to obtain this value is to turn the plate 180° from its original orientation and measure it again, always setting in each coordinate in the direction of increasing numbers on the scale, except that again, the comet is measured before and after the reference stars in each coordinate, and the mean of these measures also goes into the position computation. It is traditional to call the first measures "Direct" and those 180° from them "Reverse", and to affix subscripts "d" and "r", respectively, to the coordinate labels. So the first measures recorded by X_d and Y_d; those 180° from the first become X_r and Y_r (with the one exception discussed below).

When measurement of the plate has been completed, don't be in a hurry to take it off the measuring engine. Leave it in place until all checking processes described below have been completed. The individual star and comet measures, which have been written down as they were made, should be averaged and recorded, along with their star numbers, on a computing sheet, in columns labelled "Number", "X_d", "Y_d", "X_r" and "Y_r". Then, if we define:

$$x' = \tfrac{1}{2}(X_d - X_r) \qquad (1)$$

and

$$y' = \tfrac{1}{2}(Y_d - Y_d) \qquad (2)$$

we have coordinates of each star with respect to the center of the turntable of the measuring engine. If we also have x'_c and y'_c, coordinates of the plate center with respect to the turntable center, we can subtract these coordinates, respectively, from x' and y' for each star to determine x and y, coordinates of each star referred to the center of the plate. It is quite helpful in this process to have a center star measured to provide x'_c and y'_c; its celestial coordinates can then go into the plate reduction as the plate center as well. These steps should be included in a well-programmed Turner Reduction computer program.

X-Y engines are so laid out that when a plate is mounted emulsion-side-up on the stage, with the east side toward increasing X readings, the north side will be toward increasing Y readings if the plate was taken with a refractor or a prime-focus reflector, including Schmidt telescopes -- or Schmidt-Cassegrains, for that matter. Then the designations of X_d and Y_d, X_r and Y_r as pairs measured together, still are valid. The exception mentioned above is the plate taken at the Newtonian or other folded focus of a telescope. Then North lies toward <u>decreasing</u> Y values when East is toward increasing X. One measures these plates on an X-Y engine just like any others, designating the settings as X and Y. When the subscripts are applied, however, the first pair of measures is designated X_d and Y_r; the second pair becomes X_r and Y_d. The Turner Reduction works perfectly as long as the person feeding the computer is careful to put the real X_d and X_r and Y_d and Y_r into the computer together and in the proper order. The problem does not occur with X engines; one simply takes care to rotate the turntable so that North lies in the direction of increasing scale numbers after measuring X_d.

There are two additional benefits arising from measurement of images in Direct and Reverse. One involves the systematic errors, varying with magnitude of reference stars, mentioned earlier in connection with Table 2. Suppose the measurer regularly mis-bisects a given star image by an amount ϵ (which may be positive or negative). If the true center measures for that star in Direct and Reverse for the same coordinate are D and R, the measurer will systematically set on $D + \epsilon$ and $R + \epsilon$ when he measures that image in Direct and Reverse. When the measures are related to the turntable center by Equations (1) and (2), we find that in the subtraction of the form (X_d - X_r) or (Y_d - Y_r), we obtain ($D - \epsilon$) - ($R - \epsilon$) = D - R, the difference of the true center settings, the systematic errors having been cancelled in the subtraction. For this reason, it is important that the measurer should develop a consistent pattern of systematic errors, rather than that he/she sweat and strain to make the bisection accurate to the last half-μm.

The other benefit provided by Direct and Reverse measures is a check upon the accuracy with which the measures have been recorded, and later, a check on the accuracy with which they are keyed into the computer for the reduction, if the reduction is programmed to execute this check. The check is as follows: for each image, comet or reference star, we have measures X_d, Y_d, X_r and Y_r. We can add these measures to obtain sums S_x and S_y, for each image:

$$X_d + X_r = S_x \tag{3}$$

and

$$Y_d + Y_r = S_y \tag{4}$$

If these sums are recorded for each image, it will be seen that all of the sums S_x will be similar, and all of the sums S_y will be similar within not too many μm, if the plate has been rotated by exactly 180° between Direct and Reverse measures. A trend of sums in one coordinate, say S_y decreasing as X increases, indicates that the rotation was not exactly 180°. This is not a serious problem. Its effects are linear, and the Turner Reduction will absorb all linear effects. A difference of 20 or 30 μm between S_x or S_y for some reference star and the corresponding sum for the comet or between brighter reference stars and fainter ones is not serious, either; it merely demonstrates the different systematic errors in measurement between the different images. Those differences will be largely subtracted out, as described above. S_x will not necessarily be equal to S_y for measures on an X-Y engine; they may show differences of 100 mm or more! The sums should be nearly equal for an X engine, since the same screw is measuring both coordinates.

When performing this check at the end of measuring a plate, it is most helpful to do it on a simple electronic calculator. One's eye can be dulled by too many numbers passing by, so that errors are not caught. It helps to have the integer portion of each of the sums stored in separate registers of the calculator. After adding each Direct and Reverse pair of measures, subtract the appropriate register from the sum, recording on paper only what is left. This check should take place before the plate is removed from the stage of the measuring engine. If an error is detected or suspected, the measurer can go back and check the setting(s) on that image in the Reverse orientation. The most common errors are mis-readings or mis-recordings by 0.5, 0.1, 1 or several mm. The correction of such an error should be at that level of accuracy; anything smaller may be a systematic error arising from the size of the image and should not be changed. Check all suspicious stars, make any corrections which may show up, and if any sum still looks strange, re-orient the plate in the Direct configuration and look at the suspicious settings in that direction. If no reading or copying error is found, and the same image has been measured in Direct as was measured in Reverse, accept the measure provisionally as accurate and see how that star behaves in the reduction.

The reduction program should be programmed to execute this check as the numbers are entered from the computer keyboard or keypad. If a different sum appears, the program should provide for a return to the point where the numbers were keyed in so that the input may be done over carefully and correctly. If it still does not agree with the earlier value, there may be an error in the earlier sum. This should be apparent by inspection at this point. This is a better way to check the accuracy of the keyboard work than the duplicate entry of the data, which is the most simple-minded method of checking, and the method most susceptible to making the same error twice in succession if it is made once, or making a new error the second time around, to add confusion to the process.

If the measurer can reduce the measures on the spot, it is better to leave the plate on the measuring engine until the reduction is satisfactorily completed. If there are other plates to be measured and the measures must be reduced at another site, a plate can be taken off the measuring engine as soon as the measurer is satisfied with the accuracy of the transcription of the measures, as shown by the results of Direct + Reverse check. The plate (or film) should be placed into an appropriate envelope, properly labelled, and retained.

TRAINING MADE EASY!

But before there are reductions, there must be measures; before there are measures, the measurer must learn the art. This eye-brain-hand coordination is best developed by sitting down at the measuring engine and measuring. Start with a few plates taken at sidereal rate, so the star images are round and the trail of the moving object is not overly long. It may be easier for the novice to learn on an X engine, since then he/she can concentrate on bisecting the image in one dimension at a time and develop some confidence in the bisection estimates. The Guidelines for Measurers (Table 2) should be kept in mind as one measures and works toward greater facility in measuring.

After bisecting a few dozen round star images, the novice may move on to images with greater elongation. It will be probably more rewarding to start out measuring actual plates for publication, rather than some test plates that everyone else has measured already. The checks exist to detect most errors in measurement and recording, and if the plate yields strange Direct plus Reverse sums, it may be instructive to measure it again. The development of facility in measuring is partly a matter of experience and partly a development of confidence in one's own ability. With more experience in measuring large or elongated images, one may tackle slightly curved images which may still yield useful positions of objects other than Halley.

After a few hundred or a few thousand images have been measured, the measurer may wish to try his/her eye and hand at comatic images from parabolic reflectors. This will be a departure from everything learned so far, for one does not attempt to set on the center of the comatic blur when measuring such images. This may be better understood if one remembers that a short exposure of that star produces a point image corresponding to the true position of the star. Increasingly long exposures will show larger seeing discs (as with any photographic image of a star) centered on the same point, but also will show an increasingly prominent V-shaped structure extending outward, away from the center of the plate, with its apex at the true position of the star. If such an image is trailed, as the telescope tracks the motion of the comet, then one must attempt to measure the center of the trail of the point of the V, not the center of the blurred trail as a whole; the latter procedure will introduce severe magnitude-dependent errors which vary from image to image and from point to point on the plate! The measurer should attempt to select reference stars from those portions of the field where trails do not go through the V, and where both sides of the V lie at an angle to the direction of trailing. Otherwise, it will be difficult to tell where the trail of the point of the V begins or ends.

Another challenge to the experienced measurer is the derivation of useful positions from plates with images classified as no better than semi-accurate in Table 1. If the comet or asteroid image is round, and the star trails are straight, one may assume that the position of the moving object at the beginning of an exposure corresponds to the position of the star at the beginning of its trail. If the star trail tapers or is cut down by clouds, one may still attempt to set the cross-hairs on the center of curvature at the beginning of the trail. If this is done in Direct and Reverse, one may hope to minimize systematic errors in the estimate of the position of the center of curvature. The Direct plus Reverse sums will give an indication of how successfully this has been accomplished. The resulting positions, of course, should be reported as of the time at which the exposure began, and with the qualification, "Beginnings of star trails measured." This raises them from "Semi-accurate" to "Less accurate" positions!

Another challenge to the experienced measurer is the star trail which is uniform in width but is smoothly curved, which can be described as short arcs of moderately long-radius circles. The corresponding trail of a moving object will be elongated, parallel to the radius of the circle that goes through the center of arc. Here, one orients the plate so that one cross-hair passes through the center of both ends of the star trail, as mentioned earlier. To measure these images, one first bisects the arc. Then one tries to estimate a position for the other cross-hair, such that equal areas of the image will appear in opposite quadrants with respect to the intersection of the cross-hairs. Such measures, if succesful, can upgrade the quality of the position from "Semi-accurate" to "Less-accurate". Again, they should be reported as "Object image slightly trailed; star trails smoothly curved."

HOW GOOD IS THE MEASURING?

The measurer, particularly the novice measurer, will always want to know how accurate the measuring is. The question is not easy to answer. The Direct plus Reverse check sums for the individual reference stars and the comet may shed some light on this question immediately, but one must remember that the picture is obscured by systematic errors in setting on stars of different brightness, and between the trailed reference star images and the round images of the moving object. If the plate has not been rotated by exactly 180° between Direct and Reverse measures in both coordinates, trends in the check sums may obscure the picture even more.

The best early check comes if the reduction program provides for the computation and display of the residual for each reference star in each coordinate. The residual is computed by computing the right ascension or declination of each reference star from the measured coordinates and the plate constants determined for the plate, and subtracting from that coordinate the corresponding coordinate of the same star which was used as input data for the reduction. In practice, residuals are computed from the corresponding standard coordinates, ξ and η, and come out in microns. They can also be converted to arc seconds by the reduction program, or mentally by the measurer, if he has calculated the value of 1" in microns for his instrument.

Residuals should always be computed and inspected, because they provide the last verification of the accuracy of data input and computation. Typically, if the catalog is accurate and the measuring is good, most of the residuals should have values corresponding to a fraction of an arc second, with few near or greater than 1". If one star's residual is large, and several other stars compensate with small residuals of the opposite sign, then the data input for that one star should be examined for possible errors in the sign of a proper motion or in the position or proper motion data. If no error is found by comparing input data with the star catalog, then the catalog may be in error. The data for that star should be removed from the input data, the solution re-done, and an observed position derived for the star from the measures and plate constants. It may appear that the sign of the proper motion is wrong in the catalog, or that a 3-unit keypunch error has occurred at the $0^{\mathrm{s}}.1$ or 1" level, or that no clear-cut error can be found. If the catalog position seems to be in error by 2" or 3" or more, that star probably should be thrown out of the solution, especially if all of the remaining stars show small residuals in the new solution.

If all or many of the residuals amount to several arc seconds, or more, then something is wrong in the input data. The error or errors must be found, corrected, and the reduction redone. Otherwise, the resulting position will bear no relation to reality on the celestial sphere, and will be useless.

Because there may be errors in catalog positions and/or proper motions (no catalog is perfect!), one cannot tell from a single plate whether the residuals come from catalog or measuring inaccuracies. With two plates of the same field taken within a few days of each other, and the same reference stars measured on both, one can separate measuring from position problems. If the same star has large residuals of the same sign on both plates, that's probably a catalog error; if the size of that residual varies by a fraction of an arc second or a few μm from plate to plate, that's measuring. Differences of a few μm in residuals of a star from plate to plate show that the measuring is quite acceptable.

Residuals may also be combined by the reduction program to yield root-mean-square errors or probable errors. Instead of showing the accuracy of measurement, these quantities express the precision with which the position is related to the system of the catalog from which the reference stars were taken.

The final test of measuring accuracy must wait, perhaps for years, for the determination of the definitive orbit for the object. Then, residuals are determined with respect to the orbit for each observation. The lower the residual, the better the observation and reduction -- except that things are not clear-cut even here. A few bad observations included in the orbit solution will make everyone else's observations look worse than they really are.

When a bad position is reported for publication, it is not polite or politic to pry into how it was obtained, so little is known of the checks which have or have not been made to ensure the accuracy of the measurement and reduction. After all, everybody makes mistakes. The mark of the responsible astronomer is that mistakes don't get out of his office! If four procedures were to be carried out unfailingly by all observers on their plate measurements and reductions, bad positions might be reduced to the few cases where the wrong object is measured. These procedures are:

1. Checking for and eliminating oil film effects.

2. Measurement of both coordinates in Direct and Reverse.

3. Direct plus Reverse checking of measures, including recording and input of data into reduction program, if these steps are done by hand.

4. Calculation and inspection of reference star residuals, with correction or rejection of stars with catalog or measuring errors, followed by re-reduction of the plate.

The author acknowledges with appreciation the training received from Professors D. H. McNamara and L.E. Cunningham at Leuschner Observatory, University of California, Berkeley. Their respective courses in Practical Astronomy, especially the introduction to least squares, and in Astronomical Computing, have had the greatest practical value in succeeding years. This paper is dedicated to the memory of Hamilton Moore Jeffers (1893-1976), Astronomer at Lick

Observatory, who taught the author the techniques of moving-object astrometry and shared his last comet recovery with the author, to whom he then entrusted his comet astrometry program for the duration of the author's tenure as Assistant at Lick Observatory.

The author wishes to thank those who assisted him herein, namely: D.K. Yeomans, B. G. Marsden, H. K. Eichhorn, and U.T. Gibson, and those participating in the IHW Astrometry Net Workshop (Munich, 1984).

REFERENCES

Eckert, W. J., and Jones R. 1962. Measuring Engines. In *Astronomical Techniques*, ed. W. A. Hiltner (Chicago, Illinois: The University of Chicago Press), pp. 424-439.

Eichhorn, H. K. 1963. Ein verkürztes Verfahren zur exakten Bestimmung von Schrauben- oder Skalenfehlern und Untersuchung des Töpferschen Messapparates der Wien Universitätssternwarte. *Mitteillung der Universitäts Sternwarte*, *Wien*, 7:45

Eichhorn, H. K. 1974. *Astronomy of Star Positions*. (New York, New York: Frederick Ungar Publishing Company), pp. 81, 208.

König, A. 1962. Astrometry with Astrographs. In *Astronomical Techniques*, ed. W.A. Hiltner (Chicago, Illinois; The University of Chicago Press), pp. 463-464.

Miller, W.C. 1979. *Observatory Photographic Manual, Revised Edition*. (Pasadena, California: Pasadena City College Scholarship Fund Association).

van de Kamp, P. 1962. Astrometry with Long-Focus Telescopes. In *Astronomical Techniques*, ed. W. A. Hiltner (Chicago, Illinois: The University of Chicago Press), pp. 494-495.

DISCUSSION FOLLOWING PRESENTATION

R.M. West: Let me make a few remarks from personal experience. (1) In many places, linear glass-encoders are now used. This is a great improvement over rotational encoders and, if properly mounted, excludes backlash problems. (2) Concentric circles, in addition to the cross-wires, greatly help setting on round objects. (3) I prefer to use four settings per object. This makes it easier to judge internal accuracy and gives confidence in rejecting bad measurements. (4) Never look at the XY counter (if the positions are recorded automatically). Then you will not subconsciously try to obtain the same values in repeated settings. (5) Always remove your hand from the wheel (turning screw) between two settings. The hand may "remember" the position. (6) If possible, always leave the plate on the measuring table until the reduction is complete and successful. Errors can then be checked easily and removed.

K. Russell: I would like to urge caution in interpreting Dr. West's comment that one can forget backlash problems with measuring machines fitted with linear optical encoders. Strictly speaking, this will depend on the mechanical layout and construction and in practice there will be a small amount of backlash in many cases.

J. Gibson: I hesitate to comment upon the physical characteristics of any such system until I've used it myself. However, it seems that it should be less affected by backlash than are the familiar screw-rotation encoders. Certainly, the linear optical encoders would avoid the errors arising from oil film thickness variations from point to point on the screw.

K. Russell: On empirical evidence, I believe that the diffraction spikes on the UK Schmidt plates are a good indication of the image centroid. Do you have any indication that this might be incorrect?

J. Gibson: I have no evidence that this is incorrect for the Palomar 48 inch Schmidt, but other telescopes may have problems arising from complex diffraction patterns near the primary spikes (witness the well known picture of the Pleiades made with the 36 inch Crossley reflector at Lick). Each observer should satisfy themself that their diffraction spikes do arise from the center of the images before depending upon them implicitly.

P. Wild: It seems important to me that the whole set of reference stars and the target object should be measured twice in a symmetrical order: 1,2,...,object,...,object,...,n; then n,...,object,...,object,...,2,1. This provides some check on the development of any shifts in the meantime (e.g., by imperfect thermal adjustment of the machine). In my practice, I then average the settings and proceed with the reduction if the shift is roughly linear and on the whole less than about 5 microns (1 arcsec at our scale); otherwise, I repeat the whole measurement.

D21

N85-25036

LEAST SQUARES REDUCTION TECHNIQUE

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ABSTRACT

The algorithm for implementing a standard least squares procedure on a small computer is presented.

Fortunately for our efforts today, much of what is needed to carry out a plate reduction has been very adequately described by Marsden and Roemer (1982), and I highly recommend that everyone become familiar with that work. I will now assume that the procedures described in the previous paper have been followed to obtain a set of measures (x,y) of N reference stars plus one, or sometimes two, comet(s). I will also assume that the procedures described by Marsden and Roemer have been followed to obtain a set of standard coordinates (X,Y) for the reference stars (note the change in notation, in that I am not using Greek letters). The objective is to obtain standard coordinates (X,Y) for the comets, and then follow the steps in Marsden and Roemer to obtain the desired spherical coordinates of the comet or comets.

To begin with, I will rewrite the Marsden and Roemer equations relating standard to measured coordinates in a slightly different, slightly more rigorous way, as follows:

$$\begin{aligned} DX &= X-x = AX + BY + C \\ DY &= Y-y = A'X + B'Y + C' \end{aligned} \tag{1}$$

A, B, C, A', B', C' are known as the plate constants. This is a completely general relationship that makes no assumptions concerning rigidity or orthogonality. Note that, if the plate scale is well known and the plate is well oriented in the measuring machine, the coordinate differences are small and hence so are the plate constants. It would now seem that all we need are three reference stars to determine the plate constants, since we all know that we only need three equations to solve for the three unknowns in each coordinate. Unfortunately, the above equations are incomplete, in that they do not take into account the errors associated with each individual set of measures. Instead, these equations should be written as follows:

$$\begin{aligned} DX &= AX + BY + C + E \\ DY &= A'X + B'Y + C' + E' \end{aligned} \tag{2}$$

E and E' are the errors associated with each measure, and, unlike the plate constants, these are different for each reference star or cometary image. Two new unknowns (one in each coordinate) are introduced with each measure, meaning there will always be fewer equations than unknowns, making it impossible to solve the system rigorously. The only thing we can do is to make some assumptions about the statistics of the errors and then apply some procedure that can only estimate the values of the plate constants. That procedure is known as least squares.

Least squares makes the assumption that the observational errors are uncorrelated and that they follow the standard Gaussian error distribution. Therefore, the best estimates for the plate constants are those that minimize the sum of the calculated errors (known as residuals). We will not go into how this is derived mathematically, but the end result is to transform the 2N observational equations with 2N+6 unknowns into two sets of 3 equations with 3 unknowns, with the set for X being the following:

$$\begin{aligned} \Sigma X\cdot DX &= A\Sigma X\cdot X + B\Sigma X\cdot Y + C\Sigma X \\ \Sigma Y\cdot DX &= A\Sigma X\cdot Y + B\Sigma Y\cdot Y + C\Sigma Y \\ \Sigma DX &= A\Sigma X + B\Sigma Y + C\cdot N \end{aligned} \tag{3}$$

The set for Y is similar, with DY being substituted for DX in each equation. These are now solved, separately for X and Y, for the appropriate set of plate constants. Note that, so far, we have only been working with reference star measures, and the above summations extend over all reference stars. Of course, it is still necessary to have at least three reference stars, but this will work for the rigorous case of three reference stars and hence is perfectly general.

We now have to solve for the standard coordinates (X,Y) of the target image or images. For this, we go to the original equations without the errors, where we have two equations for the two unknowns, X and Y. To solve, we have the following steps:

$$\begin{aligned} H &= (1-A)(1-B') - A'\,B \\ X &= ((1-B')(x+C) + B(y+C'))/H \\ Y &= (A'(x+C) + (1-A)(y+C'))/H \end{aligned} \tag{4}$$

We usually want to see the resultant sums of the squares of the residuals, $\sum(E\cdot E)$ and $\sum(E'\cdot E')$, although we normally cast it in the form of the dispersion of a single measuring, corrected for biasing, as follows for X:

$$S = \sqrt{\Sigma(E\cdot E)/(N-3)} \tag{5}$$

Assuming we do not want to use up computer storage by saving all of the measures, the expression for the sums of the squares of the residuals may be given as follows for X:

$$\begin{aligned} \Sigma(E\cdot E) = {} & \Sigma(DX\cdot DX) + (A\cdot A)\Sigma(X\cdot X) + (B\cdot B)\Sigma(Y\cdot Y) \\ & + N\cdot C\cdot C - 2(A\Sigma(X\cdot DX) + B\Sigma(Y\cdot DY) + C\Sigma DX \\ & - (A\cdot B)\Sigma(X\cdot Y) - (A\cdot C)\Sigma X - (B\cdot C)\Sigma Y) \end{aligned} \tag{6}$$

This is the procedure that, with some minor modifications, has been implemented in Fortran at USNO, a copy of which was distributed with the network newsletter (with subsequent correction) concerning the Crommelin dry run. This has also been implemented in Basic on several computers, and listings are available from the network.

There are always questions of the adequacy of the plate model and the number of reference stars that should be used. Obviously, the above procedures can be extended to include non-linear terms that cover things like magnitude and color effects, coma, distortion, differential refraction, tilt, de-centering, and so on. To create one of the photographic catalogs discussed in an earlier session, such things are quite necessary. However, for cometary astrometry, it usually makes more sense to take a small region of the plate, over which the higher order effects are negligible, and use the linear model. This usually means taking at least six but not more than a dozen reference stars. We have already had a discussion of how one can identify problem situations if there are enough stars included in the solution.

Finally, a word about dependences. If the dependences are calculated to full precision directly from the measures of the reference stars and targets, the method of dependences is rigorously the method of least squares. The formulations look different, but that is only because the order in which the various summations are carried out is different. It is only when dependences are calculated approximately, either graphically, as has often been the case with comets, or using an approximate target positions, as has been done historically in parallax astrometry, that problems can arise.

REFERENCE

Marsden, B. G., and Roemer, E. 1982. Basic Information and References. In Comets, ed. L. L. Wilkening (Tucson, Arizona: The University of Arizona Press), pp. 707-733.

D22

N85-25037

REDUCTION OF ASTROMETRIC PLATES

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ABSTRACT

A rapid and accurate method for the reduction of comet or asteroid plates is described.

INTRODUCTION

When comets are being observed photographically, one is at times faced with the problem that one has to produce accurate positions within a very short time. Similar situations may occur with asteroids. At the same time no accuracy loss is desirable. In addition, the astronomers who have to solve the problem are not always familiar with astrometric procedures. In other words, we have to find a method which permits a position determination in a minimum of time, with no substantial loss of accuracy, and which is simple to handle. It is our purpose to describe such a method.

CLASSICAL PROCEDURE

Normally, if one does not want to read a position directly off a map - a procedure which is perfectly acceptable when the comet's head is large and diffuse - one identifies first a number of reference stars on the plate by a direct comparison with a map. Subsequently these stars are measured on the plate together with the comet or asteroid. The equatorial and rectangular coordinates of the reference stars are entered into a computer program which establishes the relation between the two sets of coordinates. This relation is then used to convert the rectangular coordinates. A detailed description of such a procedure for use by amateurs is given by Marsden (1982).

Depending on the type of telescope and on the accuracy required, the above mentioned procedure contains a small or a large number of coefficients or unknowns, and their number determines the minimum number of reference objects to be used. The identification of the latter turns out to be the most tedious and time-consuming part of the entire process.

OUTLINE OF THE APPROACH

First of all, while we want to make use of every reference star on the plate in order to obtain maximum accuracy, we want to reduce the task of identification to an absolute minimum, namely to two stars, of which one may even be the comet itself, if a sufficiently accurate prediction is available. The program itself will then have to find the additional reference stars.

Also we want to avoid the need of pre-correction of the measured coordinates for differential refraction, if possible. This can be done if more than two reference stars are available, and if the zenith distance is not extreme. And even if the latter is the case, quadratic terms of the refraction have little effect if the comet is reasonably well centered among the reference stars. Finally, we also have to make allowance for the possibility that the focal length of the telescope may not be accurately known.

THE PROJECTION EQUATIONS

The method which uses the conversion of plane coordinates into three dimensional rectangular coordinates, has already been mentioned in my Paper I at this Conference. For completeness we shall repeat the basic equations here. If X and Y are the measured coordinates, and F the focal length, then

tangential		concentric	
(1a)	$x = X/F$	(1b)	$x = X/F$
(2a)	$y = Y/F$	(2b)	$y = Y/F$
(3a)	$\tan r = (x^2 + y^2)^{\frac{1}{2}}$	(3b)	$r = (x^2 + y^2)^{\frac{1}{2}}$
(4a)	$u = x \cos r$	(4b)	$u = x \sin r/r$
(5a)	$v = y \cos r$	(5b)	$v = y \sin r/r$
(6a)	$w = \cos r$	(6b)	$w = \cos r$

where u, v, and w are the three dimensional coordinates.

SCALE LENGTH CORRECTION

Although the final system is not very sensitive to minor errors in the scale length F, we have to analyze first the effect of a scale error on the conversion of X, Y to u, v, w. Since the differential refraction acts primarily as a scale contraction towards the zenith, we have to expect different scale corrections for x and y. We may write instead of equations (1) and (2)

(7) $x' = x\ (1 + P_x) \qquad P_x \ll 1$

(8) $y' = y\ (1 + P_y) \qquad P_y \ll 1$

Here x' and y' are the true coordinates.

Both cos r and sin r /r are rather insensitive to variations of r, which is always a small angle, such that within reasonable limits we may neglect the variation of the w - coordinate, while u and v then vary proportionally to the respective scale corrections.

ROTATION OF COORDINATES

Let α and δ be the equatorial coordinates of a standard star, and u, v, w its transformed measured coordinates. Then, with

(9) $\xi = \sin \alpha \cos \delta$
(10) $\eta = \cos \alpha \cos \delta$
(11) $\zeta = \sin \delta$

we can expect the relations

(12) $\xi = a_{11} u + a_{12} v + a_{13} w$
(13) $\eta = a_{21} u + a_{22} v + a_{23} w$
(14) $\zeta = a_{31} u + a_{32} v + a_{33} w$

In the absence of deformations or scale errors the matrix (a) will be an orthogonal rotation matrix, and its elements may be expressed as functions of the three angles A, B, and C. Evidently, with three reference stars the nine unknowns of the equations (12) - (14) can be determined. A least square method can be used if the number of references stars is larger than three. In this process no orthogonality is imposed, such that scale errors as indicated in equations (7) and (8) will cause that

$$\sum_{i=1}^{3} a_{i1}^2 \neq 1$$

$$\sum_{i=1}^{3} a_{i2}^2 \neq 1$$

and in fact, the values of P_x and P_y can be determined from the above sums.

At this point it is important to note that the solution of the above system does not require previous knowledge of the equatorial coordinates of the plate center.

LINEARIZATION

Substituting the scale errors P_x and P_y, we have, instead of equations (12) - (14)

(15) $\xi = a_{11} (1 + P_x) u + a_{12} (1 + P_y) v + a_{13} w$
(16) $\eta = a_{21} (1 + P_x) u + a_{22} (1 + P_y) v + a_{23} w$
(17) $\zeta = a_{31} (1 + P_x) u + a_{32} (1 + P_y) v + a_{33} w$

where it is assumed that P_x and P_y are small enough such that their effect on the w - coordinates is negligible. These equations contain five unknowns, namely A, B, C, P_x, and P_y.

The three angles appear in a nonlinear form. The equations may be linearized as follows: we adopt initial values for the five unknowns, i.e. A_o, B_o, C_o, P_{xo}, and P_{yo}. Furthermore, let qijA be the partial derivative of aij with respect to A, and similar terms for the derivatives with respect to B and C. With the initial values for the angles we calculate the elements of the matrix (a) and its partial derivatives. Furthermore, we write

$$(18) \quad u' = u\,(1 + P_{xo})$$
$$(19) \quad v' = v\,(1 + P_{yo})$$

and then have

$$\begin{aligned}(20) \quad \xi = {} & a_{11}\,u' + a_{12}\,v' + a_{13}\,w \\ & + (q_{11A}\,u' + q_{12A}\,v' + q_{13A}\,w)\,\Delta A \\ & + (q_{11B}\,u' + q_{12B}\,v' + q_{13B}\,w)\,\Delta B \\ & + (q_{11C}\,u' + q_{12C}\,v' + q_{13C}\,w)\,\Delta C \\ & + a_{11}\,u\,\Delta P_x \\ & + a_{12}\,v\,\Delta P_y\end{aligned}$$

and similar equations for η and ζ.

Subsequently

$$(21) \quad A_1 = A_o + \Delta A$$
$$(22) \quad B_1 = B_o + \Delta B$$
$$(23) \quad C_1 = C_o + \Delta C$$
$$(24) \quad P_{x1} = \Delta P_x$$
$$(25) \quad P_{y1} = \Delta P_y$$

With these improved values for the unknowns we repeat the process from equation (18) on. As initial values we use

A_o = approximate right ascension of plate center
B_o = approximate declination of plate center
$C_o = P_{xo} = P_{yo} = 0$

Since for each reference star three equations are obtained, the system can be solved with a total of two reference stars.

SEARCH FOR ADDITIONAL REFERENCE STARS

To add more to the two initial reference stars, two ways are open:

1. When measuring the plate, stars are added which on the basis of their magnitude may be expected to be in the reference catalogue, or
2. From the reference catalogue, using the inverse matrix of (a), plate coordinates are predicted and measured.

In both cases, identities are subsequently established in the following manner: all measured plate coordinates are converted into equatorial coordinates using the matrix (a), and are mixed with the catalogue coordinates. The programs OK and ID of paper I will then find all pairs.

FINAL SOLUTION

When the total number of reference stars after the search program exceeds two, the values of the coefficients of equations

(12) - (14) can be calculated, irrespective of whether the resulting matrix is orthogonal or not. If no additional stars were found, the original two-star solution has to be used.

Finally, with ξ, η, and ζ for the comet or asteroid its right ascension and declination can be calculated from

$$(26) \quad \tan\delta = \frac{\zeta}{(\xi^2 + \eta^2)^{\frac{1}{2}}}$$

$$(27) \quad \tan\frac{\alpha}{2} = \frac{\xi}{\cos\delta + \eta}$$

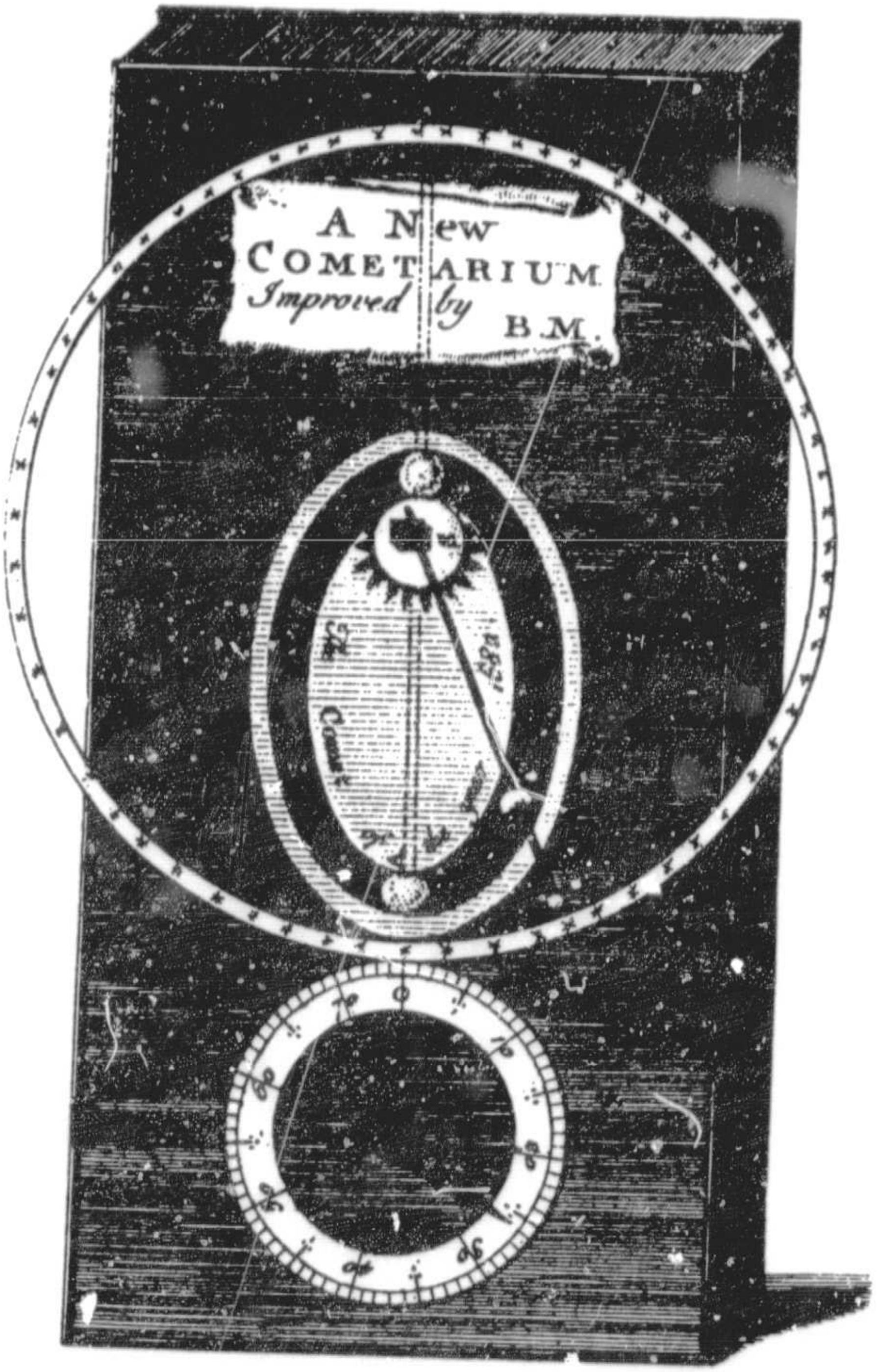
REFERENCE

Marsden, B.G., 1982, Sky and Telescope 64, p. 284.

DISCUSSION FOLLOWING PRESENTATION

L.W. Fredrick: We must use the reference stars in the Astrometry Network Special Star Catalogues. There is no point in measuring SAO stars not in these catalogues, so the stars must be identified on the plate itself.

Orbit Determination



An eighteenth century cometarium — a mechanical device showing the orbit of the comet of 1682 (Comet Halley).

COMETS AND NONGRAVITATIONAL FORCES

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ABSTRACT

A summary is given of the procedure now widely used for the allowance of nongravitational effects in the motions of comets. Some results are mentioned, and an innovative variation of the procedure is briefly discussed.

PROCEDURE

Although attempts to allow for nongravitational influences on cometary motions date back more than a century and a half, it is only during the past decade and a half that such effects have been incorporated directly into the equations of motion of a comet. This inclusion in the equations of motion is useful in that the effects of the nongravitational force can thereby be readily combined with those of gravitational forces, and the standard procedures for least-squares orbit improvement apply. Further, although the form of the equations is basically empirical, it does permit some insight into the physical nature of the force. Perhaps half a dozen individuals have participated in these computations. This paper is a brief summary of a somewhat longer recent review of the subject (Marsden 1984).

In what has come to be termed variously as "Style II" or the "standard model", it is supposed that the nongravitational force varies with heliocentric distance r according to the formula:

$$g(r) = \alpha(r/r_0)^{-m}\,[1 + (r/r_0)^n]^{-k},$$

where $\alpha = 0.1113$, $r_0 = 2.808$ AU, $m = 2.15$, $n = 5.093$ and $k = 4.6142$. The formula is based on the vaporization flux of water snow and has sometimes been adapted to the vaporization of more volatile snows by increasing the assumed value of r_0. Solutions are made for the six Keplerian orbital parameters plus the parameters A_1 and A_2 that represent the radial and transverse components of the nongravitational acceleration at unit heliocentric distance. Ideally, these solutions are made from observations covering intervals of time long enough that the parameter A_2 is at least an order of magnitude larger than its mean error and short enough that neglected possible secular changes in A_2 do not cause significant degradation of the residuals.

RESULTS

Nongravitational solutions generally have validity in attempts to link observations of a comet at three or more perihelion passages. A_1 is rarely well determined, but there is a tendency for it to be positive and an order of magnitude larger than A_2 (which can be positive or negative), and this is to be expected in terms of Whipple's (1950) icy-conglomerate model and a direction of maximum vaporization lagging behind the comet's subsolar point by a rather small amount.

There are at present 63 comets that have been observed at three or more perihelion passages. Perhaps a dozen of these comets do not show any sensible nongravitational effects. There appear to be three possible reasons for this: (a) the perihelion distance q may be significantly larger than r_0, so that the solar radiation would simply be reradiated by any water snow; (b) the comet may have lost its icy constituents; or (c) the comet's pole of rotation may be in the plane of its orbit. Reason (a) is manifested by P/Oterma, P/Smirnova-Chernykh and P/Schwassmann-Wachmann 1, all with q in the range 3-6 AU; P/Arend-Rigaux and P/Neujmin 1, which are generally of rather asteroidal appearance and are known to have rather stable orbits with q around 1.5 AU, are good illustrations of reason (b); examples of reason (c) are more difficult to establish, but P/Tsuchinshan 1, P/Holmes and P/Reinmuth 2 may be of this type. It is important to note that although both P/Holmes and P/Schwassmann-Wachmann 1 have shown considerable nongravitational activity in the form of flares in brightness, this activity does not seem to have affected the motions of these comets. The IHW test comet P/Crommelin is significant in that its motion seems to have been unaffected by nongravitational forces for the longest time, almost a century, although it is necessary to introduce a small nongravitational force in order to link the observations in 1873, 1928, 1956 and 1984; this comet appears to be active for only a very short time around perihelion ($q = 0.7$ AU) and may thus in fact illustrate the above reason (b), although reason (c) perhaps also plays a role.

About one-third of the eligible comets are known to be affected by nongravitational forces in which A_2 is either constant or decreasing rather steadily with time. These comets, which include both P/Halley and P/Encke among their number, have been considered to be in the process of deactivation (P/Arend-Rigaux and P/Neujmin 1 being in a more advanced state of this), although long-term changes in the orientation of the axes of rotation of the comets must also play some role. The existence of cases (including P/Giacobini-Zinner) where A_2 is slightly increasing is also an indication of the effect of variations in the rotation axes, and this supposition is enforced by the fact that there are also a few comets (including P/Kopff) where A_2 has been observed to go through zero. One should try and distinguish between these cases and those where more violent changes in A_2 have been observed to take place: such changes, illustrated by P/Brorsen and P/Perrine-Mrkos, are what might be expected to happen if a comet is in the process of complete disintegration (so that there will be no asteroidal remnant).

There are a dozen or so three-apparition comets still in need of study. Nongravitational effects are apparent in the motions of a handful of two-apparition comets, notably P/Westphal and P/Gale, which have perhaps also disintegrated.

One can also occasionally determine meaningful radial nongravitational parameters for long-period comets observed at a single apparition. In fact, by recognizing that a positive A_1 is present (even if it cannot be detected) and noting the correlation between A_1 and the reciprocal of the orbital semimajor axis, one can conclude that the observed extent of the Oort cloud is scarcely more than 50 000 AU and that the few existing hyperbolic determinations of original orbits are almost certainly fictitious.

INNOVATION

Rickman and Froeschlé (1982) have shown that attempts to model the distribution of temperature over a cometary nucleus can lead to variations of nongravitational force that depart substantially from the function g(r). They suggest that, instead of following an inverse-square law near the sun, the transverse component of the force may be essentially constant, and that the variations occurring as the transition distance r_0 is approached depend very strongly on the comet's thermal inertia and rotation period. Landgraf (1984) has very recently applied the Rickman-Froeschlé theory in detail to P/Halley and obtained values of A_2 ranging by over a <u>factor</u> of six. Experimentation of this type is certainly very much to be encouraged, although it seems doubtful that one could produce a single model that could be used for a large number of comets and involve the determination of a reasonably small number of nongravitational parameters unique to each comet. The "standard model", while it may not be completely realistic, is convenient to use and certainly yields considerably better descriptions of cometary motions than does reliance on purely gravitational principles. It also permits one to make some kind of reasonable comparison of one comet with another.

REFERENCES

Landgraf, W. 1984. On the motion of comet Halley. In press.

Marsden, B. G. 1984. Nongravitational forces on comets: the first fifteen years. In <u>Dynamics of Comets</u>, Proc. IAU Colloq. No. 83, ed. A. Carusi and G. B. Valsecchi (Dordrecht, The Netherlands: Reidel), in press.

Rickman, H. and Froeschlé, C. 1982. Thermal model of comet Halley. In <u>Cometary Exploration</u>, ed. T. I. Gombosi (Budapest, Hungary: Hungarian Academy of Sciences), vol. 3, p. 109.

Whipple, F. L. 1950. A comet model. I. The acceleration of Comet Encke. <u>Astrophysical Journal</u>. 111:375.

DISCUSSION FOLLOWING PRESENTATION

L.G. Bowell: Can one go so far as to say that for the ephemeris requirements of P/Halley, the way nongravitational effects are modeled is not critical?

B.G. Marsden: I don't think there is any problem with the positions projected on the plane of the sky, particularly if updates incorporating the latest astrometric data are available. On the other hand, we may be deluding ourselves as far as the range to the comet is concerned, and that is why it is important to try to have the data from the Soviet probes available for the Giotto encounter.

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THE ORBITS OF COMETS HALLEY AND GIACOBINI-ZINNER

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ABSTRACT

The ongoing activities to improve the orbits and ephemerides of comets Halley and Giacobini-Zinner are outlined. The nongravitational acceleration model of Marsden et al (1973) is used to represent the motion of these two comets over their observed intervals, and recent orbital updates are presented.

NONGRAVITATIONAL FORCES AND COMET HALLEY

Beginning with the work of Bessel (1835,1836), it became clear that the motion of comet Halley was influenced by more than the solar and planetary gravitational accelerations. Michielsen (1968) pointed out that perihelion passage time predictions that had been based upon strictly gravitational perturbation calculations required a correction of +4.4 days over the past several revolutions. Kiang (1972) determined a mean correction of +4.1 days.

In introducing the icy conglomerate model for a cometary nucleus, Whipple (1950,1951) recognized that comets may undergo substantial perturbations due to reactive forces or rocket-like effects acting upon the cometary nucleus itself. In an effort to accurately represent the motions of many short periodic comets, Marsden (1968,1969) began to model the nongravitational forces with a radial and transverse nongravitational acceleration term in the comet's equations of motion. Marsden et al (1973) modified the nongravitational force terms to represent the vaporization flux of water ice as a function of heliocentric distance. The cometary equations of motion are written;

$$\frac{d^2\vec{r}}{dt^2} = -\mu\frac{\vec{r}}{r^3} + \frac{\partial R}{\partial \vec{r}} + A1\ g(r)\hat{r} + A2\ g(r)\ \hat{T} \qquad (1)$$

$$\text{where } g(r) = \alpha\,(r/r_0)^{-m}\,(1 + (r/r_0)^n\,)^{-k}$$

The acceleration is given in astronomical units/(ephemeris day)^2; μ is the product of the gravitational constant and the solar mass, while R is the planetary disturbing function. The scale distance r_0 is the heliocentric distance where reradiation of solar energy begins to dominate the use of this energy for vaporizing the comet's nuclear ices. For water ice, r_0 = 2.808 AU and the normalizing constant α = 0.111262. The exponents m,n,k equal 2.15, 5.093 and 4.6142 respectively. The nongravitational acceleration is represented by a radial term, A1 g(r) and a transverse term, A2 g(r), in the equations of motion. If the comet's nucleus were not rotating, the outgassing would always be preferentially

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toward the sun and the resulting nongravitational acceleration would act only in the antisolar direction. However, the rotation of the nucleus, coupled with a thermal lag angle (θ) between the nucleus subsolar point and the point on the nucleus where there is maximum outgassing, introduces a transverse acceleration component in either the direction of the comet's motion or contrary to it - depending upon the nucleus rotation direction. The radial unit vector ($\hat{r}$) is defined outward along the sun-comet vector, while the transverse unit vector ($\hat{T}$) is directed normal to $\hat{r}$ in the orbit plane and in the direction of the comet's motion. An acceleration component normal to the orbit plane is certainly present for most comets but its periodic nature makes detection difficult in these computations because we are solving for an average nongravitational acceleration over three or more apparitions. While the nongravitational acceleration term $g(r)$ was originally established for water ice, Marsden et al (1973) have shown that if the Bond albedo in the visible range equals the infrared albedo, then the scale distance r is inversely proportional to the square of the vaporization heat of the volatile substance.

Using observations of comet Halley over the 1607-1911 interval, Yeomans (1977) used a least squares differential correction process to solve for the six initial orbital elements and the two nongravitational parameters A1 and A2. Different values for the scaling distance were tried with the result that $r = 2.808$ AU was the optimum input value. This suggests that the outgassing causing the nongravitational forces acting on comet Halley are consistent with the vaporization of water ice. This result is a general one for nearly all comets for which nongravitational force parameters have been determined. The positive sign for the determined value of A2 for comet Halley indicates that there is a nongravitational acceleration component acting in the direction of the comet's orbital motion and that the nucleus of comet Halley is rotating in a direct sense - in the same direction as the orbital motion. Yeomans (1977) integrated the motion of comet Halley back to 837, and forward to predict a perihelion passage time of 1986 Feb. 9.66.

Yeomans and Kiang (1981) began their investigation into comet Halley's past motion with an orbit based upon the 1759, 1682 and 1607 observations of comet Halley. They then numerically integrated the comet's motion back to 1404 B.C. Planetary and nongravitational perturbations were taken into account at each half day integration step. In nine cases, the perihelion passage times calculated by Kiang (1972) from Chinese observations were redetermined and the unusually accurate observed perihelion times in 837, 374 and 141 A.D. were used to constrain the computed motion of the comet. The dynamic model, including terms for nongravitational effects, successfully represented all the existing Chinese observations of comet Halley. This model assumed the comet's nongravitational forces remained constant with time; hence it seems that the comet's spin axis has remained stable, without precessional motion, for more than two millennia. Also implied is the relative constancy, over two millennia, of comet Halley's ability to outgas. This latter result is consistent with the comet's nearly constant intrinsic brightness over roughly the same interval (Broughton, 1979; Hughes, 1983).

From the list of Halley's orbital elements given by Yeomans and Kiang (1981) from 1404 B.C. to 1910 A.D., one can make a crude estimate of Halley's minimum dynamic age. The heliocentric distance to the comet's descending node increased from 0.85 AU in 1910 to 1.74 AU in 1404 B.C. If this rate of increase continued back into the distant past then the comet could not have crossed the ecliptic plane near Jupiter's orbit until 14,300 B.C. If Jupiter happened to be near during this nodal crossing, then perhaps comet Halley was captured into its current orbit configuration. Hence in 1986, comet Halley will have been in its current orbit for at least 16,000 years and probably much longer.

RECENT ORBITAL WORK ON COMET HALLEY

The recovery of comet Halley on October 16, 1982 at Mt. Palomar showed the comet's image to be only 9 arc seconds away from the ephemeris position provided by Yeomans (Jewitt et al, 1982). At this writing there have been additional accurate astrometric positions provided by astronomers at Kitt Peak Observatory in Arizona, the Canada-France-Hawaii Telescope in Hawaii and from the European Southern Observatory at La Silla, Chile. Recovered at a distance of more than 11 AU from the sun, the comet showed no obvious activity and the initial observational accuracy is not limited by the uncertainty of the comet's center of mass within an extensive coma. The initial astrometric positions of comet Halley are generally accurate to within 1 arc second with a series of 25 positions from La Silla in late January 1984 achieving a heretofore unrealizable root mean square accuracy of less than 0.5 arc seconds in both right ascension and declination.

There are also efforts underway to improve the accuracy of the older data. Morley (1983) has used the SAO star catalog to improve upon the positions taken at Cordoba during the last apparition, Klare et al (1983) have remeasured some of the 1909-11 Heidelberg plates and Bowell (1982) has remeasured some 1910-11 Lowell Observatory plates that were never used for astrometric positions before. Pereyra and West (1984) have remeasured approximately 70 plates taken at Cordoba, Argentina in 1910 and Gibson (1984) is remeasuring several 1910-11 plates taken at the Yerkes Observatory in Williams Bay Wisconsin. Roser (1984) has re-reduced much of the 1835-36 visual data on comet Halley using modern reference star catalogs.

Within the Astrometry Network of The International Halley Watch, the computer software for cometary orbit determination has been improved somewhat. Incoming observations times in UTC are reduced to ephemeris time, the observatory's coordinates are assigned and the right ascension and declination are corrected for the small effects of elliptic aberration. Once verified and weighted the observations are stored in reverse chronological order on the master data file for use by the orbit determination program. This latter program takes into account the comet's nongravitational perturbations, as well as the planetary perturbations at each time step. The local error allowed at each time step can be input and the time steps of the numerical integration vary to limit the local error to the input tolerance. All computations are done in double precision giving 16 significant figures on JPL's Univac computer. The partial derivatives of the observables are numerically integrated along with the comet's equations of motion. To be consistent with the reference frames used by the various flight projects to comets Halley and Giacobini-Zinner, the comet's equations of motion also include general relativistic effects by means of the parameterized space-time metric of the Eddington-Robertson-Schiff formalism. Currently this program uses a batch processed, weighted least squares technique for the orbit determination. The program can store and use a priori information matrices and map covariance matrices to specified epochs. For example, the improved orbit determination program was used to establish a prediction for the 1986 perihelion passage time based upon a new fit to the data from the 1759,1835 and 1910 returns. If this program had been available prior to the comet's recovery, the predicted time of perihelion passage would have been 1986 Feb. 9.486. At this writing, the most recent orbit for comet Halley is based upon 751 observations over the interval from Aug. 21, 1835 to Mar. 4, 1984. The weighted and unweighted RMS residuals are 1.94" and 2.81" respectively. At this writing, the most recent set of osculating orbital elements (IHW orbit #16) are;

Epoch	1986 Feb. 19.0 E.T.
Perihelion	1986 Feb. 9.43881 E.T.
q (AU)	0.5870992
e	0.9672724
w	111.84657
node	58.14397
I	162.23932
A1	0.1471
A2	0.0155

The angular elements are referred to the ecliptic plane and the mean equinox of 1950.0 and the nongravitational parameters are given in units of 10^{-8} AU/(ephemeris day)^2. Table 1 presents the perihelion passage times for each of three orbits and Table 2 gives the corresponding nongravitational parameters. The respective columns in Table 1 represent the orbit number, the interval and number of observations used in each orbit solution, the root mean square (RMS) residual in arc seconds, the weighted RMS residual in arc seconds and the perihelion times for the indicated apparitions. The "observed" perihelion passage times given on line four of Table 1 are taken from the paper of Yeomans and Kiang (1981). In Table 2, the radial (A1) and transverse (A2) nongravitational parameters are given along with their formal RMS uncertainties. One must remember that these RMS uncertainties are always optimistic since they include only the effect of the observation noise and not errors in the nongravitational model itself.

It is evident from Table 2 that the nongravitational parameter A2 is far better determined than A1 and that A2 is essentially constant with time. This latter result is also evident from Table 1 where the differences between the "observed" and computed times of perihelion passage are very small indeed. For example, the 1986 time of perihelion passage is predicted by orbit No.2 to be 1986 Feb. 9.4859 whereas the "observed" value (from orbit No.1) is Feb. 9.4388. If there were a time dependence in the nongravitational accelerations, this type of close agreement would not be possible. In fact the signs and magnitudes of the various differences between the "observed" and computed times of perihelion passage do not support even a slight time dependence in the nongravitational parameters. This result confirms the previous result of Yeomans and Kiang (1981). The excellent agreement between the predicted and "observed" times of perihelion passage shown in Table 1 suggests that orbit number 1 can be integrated forward to give an idea as to the future perihelion passage times for comet Halley. For example, the next two predicted times of perihelion passage are 2061 July 28.6918 and 2134 March 27.6849. The latter apparition will include a close earth approach down to 0.09 AU on May 7, 2134. Our great-great grandchildren should have plenty of time to prepare themselves.

Table 1. Perihelion Passage Times For Comet Halley Orbital Solutions

No.	Observ. Interval	No. Obs	RMS Res	WGT RMS Res	1986 Feb.	1910 May	1835 Nov.	1759 Mar.	1682 Sep.	1607 Oct.
1	1984-1835	751	2.81	1.94	9.4388	20.1785	16.4396	13.020		
2	1911-1759	718	12.1	2.51	9.4859	20.1785	16.4396	13.062	15.369	
3	1836-1682	278	23.5	5.4		20.1120	16.4396	13.062	15.279	27.548
								13.061	15.281	27.541

Table 2. Nongravitational Parameters for Comet Halley Orbit Solutions

No.	A1 x 10^8		A2 x 10^8	
1	+0.1471	+/- 0.0195	+0.015460	+/- 0.000017
2	+0.1083	0.0217	+0.015683	0.000017
3	-0.0081	0.1087	+0.015324	0.000017

Alternate nongravitational force models have been tried in an effort to improve upon the existing model developed by Marsden et al (1973). Gas production rates computed by Divine(1982) were evaluated at each integration step using a comet centered rocket-like thrust direction as denoted by Sekanina (1981). Thus, this new model allowed for a comet outgassing at a rate that followed the visual light curve and was asymmetric with respect to perihelion. In addition the thermal lag angle(Θ), spin pole inclination(I), and the direction of the comet's subsolar point at perihelion(Φ) were variables in the model testing procedure. The attempted solutions proved to be insensitive to input values of ϕ and although the final solutions were not completely satisfactory, the optimum values for the spin pole inclination and thermal lag angle were approximately 30 and 5 degrees respectively. No combination of the input variable values could improve upon the existing nongravitational force model of Marsden et al (1973). It seems likely that additional improvements in the solutions using this alternate nongravitational force model will have to await information on the spin pole orientation expected from the Halley flight projects in March 1986.

NONGRAVITATIONAL FORCES AND COMET GIACOBINI-ZINNER

Periodic comet Giacobini-Zinner was discovered at Nice in late 1900 by Giacobini and it was accidentally rediscovered by E. Zinner at Bamberg in 1913. With a period of 6.5 years, the comet has a favorable return approximately every 13 years. The comet was poorly observed at three perihelion passages (1940,1966,1979) and missed altogether in 1907, 1920 and 1953. Yeomans(1971) concluded that the nongravitational accelerations acting upon this comet were increasing slightly with time and although these nongravitational accelerations were smoothly varying prior to 1965, this was not the case if the 1965 observations were included in the orbital solutions.

Recently we updated the earlier work of Yeomans(1971) using the nongravitational acceleration model of Marsden et al (1973) and including the observations made during the three most recent apparitions in 1972, 1979 and 1984. A total of 251 observations were used over the interval December 25, 1900 through the recent recovery observations made at Kitt Peak observatory on April 3, 1984. In addition to the 4 Kitt Peak observations reported for April 3, 1984 we included a pre-recovery observation taken on January 28, 1984 at the ESO telescope at La Silla, Chile and 2 observations made at Cerro Tololo, Chile on July 21, 1984. Each of the observations were weighted equally and the following elements (IHW orbit #10) represent the most recent orbital results for comet Giacobini-Zinner;

Epoch	1985 Sept. 12.0 E.T.
Perihelion	1985 Sept. 5.24907 E.T.
q (AU)	1.0282614
e	0.7075300
W	172.48887
node	194.70595
I	31.87829
A1	-0.0543
A2	-0.0465

Table 3 presents recent results on several 3 apparition orbit solutions for comet Giacobini-Zinner.

Table 3. Nongravitational Parameters for Comet Giacobini-Zinner Solutions

No.	Observ. Interval	No. Obs.	RMS Res.	$A1 \times 10^8$		$A2 \times 10^8$	
1	1984-1972	84	1.17	-0.0543	+/- 0.0913	-0.0465	+/- 0.0034
2	1978-1965	82	1.21	-0.1624	0.1245	-0.0463	0.0013
3	1973-1959	119	1.60	0.3302	0.0174	0.0241	0.0015
4	1965-1946	87	2.63	0.4388	0.0232	0.1322	0.0009
5	1960-1939	84	1.15	0.2856	0.0105	0.0393	0.0004
6	1947-1933	61	1.38	0.1253	0.0366	0.0387	0.0016
7	1939-1926	29	2.15	0.4090	0.2352	0.0324	0.0025
8	1933-1913	62	2.02	0.1544	0.0485	0.0345	0.0002
9	1927-1900	57	2.19	0.1043	0.0662	0.0349	0.0001

Orbit number 2 in the above Table 3 was used to provide the successful search ephemeris for comet Giacobini-Zinner and the predicted time of perihelion passage time in 1985 required a correction of only +0.01 day once the comet was recovered (Yeomans, 1983: Djorgovski et al, 1984). From the values of A2 in Table 3, one can say that the comet's nucleus was rotating in a direct sense without substantial precessional motion of the spin pole over the period from its discovery in 1900 to the 1959 apparition. However, as soon as orbital solutions were attempted using the 1965 data, the RMS residual increased and the value of A2 changed substantially. In orbit 4, the high RMS residual value suggests that the determined value of A2 may not be too meaningful. If one ignores orbit 4 then one can see a decrease in the value of A2 from a positive and nearly constant value through the 1959 apparition to a decreasing and eventually negative value after 1959. This behavior strongly suggests that the spin axis of the comet was severely perturbed around 1959 and the spin axis subsequently passed through the comet's orbit plane. Prior to approximately 1965, the comet was rotating in a direct sense whereas it may now be rotating in a retrograde fashion.

SUMMARY AND CONCLUSIONS

1. Recent orbital work on comet Halley has shown that there is no evidence to suggest that the transverse nongravitational parameter (A2) has not remained constant over the comet's observed interval. This suggests that over two millennia, the comet's nucleus (rotating in a direct sense) has not suffered an appreciable loss in its ability to outgas nor has the spin pole shown any obvious precessional motion.

2. For comet Giacobini-Zinner, the nongravitational parameter, A2, changed sign around the 1959 apparition suggesting that the comet's spin pole has precessed through the comet's orbit plane and the nucleus' rotation has evolved from a direct to a retrograde rotator.

3. Attempts to improve upon the nongravitational acceleration model of Marsden et al (1973) have not yet been successful.

4. As pointed out by Morley (1984), the introduction of additional "solve for" variables into the weighted least squares process can effectively reduce the final RMS residuals but unless these variables are physically meaningful, the predictive capability of the resultant solutioncan be degraded. Consecutive 3 apparition solutions, such as those presented in Tables 1,2 and 3, are the best techniques for examining the time dependence of nongravitational parameters. The existing nongravitational force model is not perfect so that the best solutions for short term predictions will likely result from a data arc that is short enough such that neglected secular changes in A2 do not cause significant degradation of the orbit residuals (Marsden, 1984).

5. For identical data sets, comparisons between Halley orbits computed at JPL and at ESOC do not show significant differences (Morley, 1984) and although the the ongoing work at Moscow (Savchenko, 1984) uses 5 apparition solutions rather than 3 apparition solutions, their results are similar to long arc solutions at both JPL and ESOC.

6. The acquisition of future, high quality astrometric data, along with the ongoing work to improve the older comet Halley observations, will allow the continued improvement in the orbital calculations for comets Halley and Giacobini-Zinner.

REFERENCES

Bessel, F.W. 1835. Schreiben des Herrn Geheimenraths und Ritters Bessel an den Herausgeber. Astron. Nachr. 13:3-6.

Bessel, F.W. 1836. Bemerkungen uber Mogliche Unzulanglichkeit der die Anziehungen Allein Beruchsichtigenden Theorie der Kometen. Astron. Nachr. 13:345-350.

Bowell, E. 1982. Minor Planet Circular 6841, dated 1982 May 8.

Broughton, R.P. 1979. The Visibility of Halley's Comet. J. Roy. Astron. Soc. Can. 73:24-36.

Divine, N. 1982. Revised Light Curve and Gas Production Rate for Comet Halley. JPL Interoffice Memorandum 5137-82-101, dated June 15,1982.

Djorgovski,S., Spinrad,H., Will,G. and Belton,M.J.S. 1984. I.A.U. Circular 3937 dated 1984 April 12.

Gibson, J. 1984. Work in Progress.

Hughes, D.W. 1983. Temporal Variations of the Absolute Magnitude of Halley's Comet. Mon. Not. Roy. Astron. Soc. 204:1291-1295.

Jewitt,D.C., Danielson,G.E., Gunn,J.E., Westphal,J.A., Schneider,D.P., Dressler,A., Schmidt,M., and Zimmerman,B.A. (1982) I.A.U. Circular 3737.

Kiang,T. 1972. The Past Orbit of Halley's Comet. Mem. Roy. Astron. Soc. 76:27-66.

Klare, G., Roser, S., Schwehm, G. and West, R. 1983. Personal communication dated Dec. 13, 1983.

Marsden,B.G. 1968. Comets and Nongravitational Forces. *Astron. J.* 73:367-379.

Marsden,B.G. 1969. Comets and Nongravitational Forces.II. *Astron. J.* 74:720-734.

Marsden,B.G. 1984. Comets and Nongravitational Forces. These Proceedings.

Marsden,B.G., Sekanina,Z. and Yeomans,D.K. 1973. Comets and Nongravitational Forces. V. *Astron. J.* 78:211-225.

Michielsen,H.F. 1968. A Rendezvous with Halley's Comet. *J. Spacecr. Rockets* 5:328-334.

Morley,T.A. 1983. Re-Evaluation of the Observations of Comet Halley. Giotto Study Note No. 46. dated Nov. 1983.

Morley,T.A. 1984. The Work on Comet Halley's Orbit at ESOC. These Proceedings.

Pereyra, Z.M. and West, R.M. 1984. Private Communication.

Roser, S. 1984. Work in Progress.

Savchenko, V.V. 1984. The Orbital Motion of Comet Halley. These Proceedings.

Sekanina,Z. 1981. Rotation and Precession of the Cometary Nuclei. *Ann. Rev. Earth and Plan. Sci.* 9:113-145.

Whipple,F.L. 1950. A Comet Model. I. The Acceleration of Comet Encke. *Astrophys. J.* 111:375-394.

Whipple,F.L. 1951. A Comet Model II. Physical Relations for Comets and Meteors. *Astrophys. J.* 113:464-474.

Yeomans,D.K. 1971. Nongravitational Forces Affecting the Motions of Periodic Comets Giacobini-Zinner and Borrelly. *Astron. J.* 76:83-86.

Yeomans,D.K. 1977. Comet Halley - The Orbital Motion. *Astron. J.* 82:435-440.

Yeomans,D.K. and Kiang,T. 1981. The Long Term Motion of Comet Halley. *Mon. Not. Roy. Astron. Soc.* 197:633-646.

Yeomans,D.K. 1983. *Minor Planet Circ. No. 8289.*

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THE ORBITAL MOTION OF COMET HALLEY

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ABSTRACT

Since comet Halley is to be studied with spacecraft, new requirements arise for the accuracy to which the position of the Comet is known for 1986. This paper briefly presents the methodology of constructing an exact theory, analyzes the effect of all kinds of errors in building a mathematical model of motion and the effect of a shift of Halley's center-of-mass relative to the optical center. The theory is based on the optical, angular observations of 1911 back to 1759 reduced to the mean equator and epoch of 1950.0 as well as the relative observations of 1682. The observations of 1982 have been used to control the accuracy of the theory developed. Deviations of calculated values from measured values do not exceed $1.''5$ which confirms the good degree of accuracy of this theory. The Comet's orbit is obtained using current optical data.

In the recent two decades, much information has been delivered by space vehicles about the physical and chemical composition and motion of the bodies that belong to the solar system. Comets are among the most interesting objects in the solar system. In 1986 there will be a unique opportunity for studying Comet Halley with spacecraft. There are plans to have a rendezvous with the comet near its orbit perihelion which the comet should pass on February 9, 1986 (19860209). The specified conditions of spacecraft passage relative to the comet nucleus are necessary for the approach phase. This poses rigorous constraints on the tolerable error of the spacecraft with respect to the comet's nucleus. Thus for this space experiment to be successful, comet Halley's orbital parameters must be estimated to a high accuracy. Development of the precise theory of Comet Halley's motion is one of the complex problems of celestial mechanics. With the available accuracy and possible astrometric observations, the orbital motion parameters cannot be updated using only data from the current apparition; the solution of this problem involves the study of the comet's motion in its recent apparitions, a period covering several centuries.

Comet Halley has a long history of its orbital motion studies. Not dwelling upon that history, we mention the results of the two most important investigations of its motion dynamics. Brady and Carpenter (1971) analyzed 4858 optical observations of the 4 recent Halley apparitions. An empirical secular term was introduced into the equations of motion, to account for the decreasing - with time - solar attraction. They applied an iteration trial-and-error method to determine initial conditions from the observational data. In 1977, Yeomans published a paper on the investigations of Comet Halley's orbital motion. He thoroughly selected observations in the apparitions of 1607, 1682, 1759, 1835, 1910. The equations of motion for the comet were integrated with the gravitational effect of 9 planets and disturbances of a nongravitational character taken into account. Computations were made with double precision at a step of 12 hours. Updated rectangular coordinates of the comet and the coefficients of the nongravitational acceleration were derived by the least-squares method. The predicted time of the perihelion passage 19860209.6613 was assumed from the orbit calculations using the three apparitions 1759, 1835, 1910 since this time resulted from the best r.m.s. fit of the observations.

The studies of Comet Halley's motion dynamics put forward a problem of developing a mathematical model of motion which could reproduce a true motion of the comet to a high degree of accuracy. Heliocentric coordinates of the comet were obtained by numerically integrating a system of ordinary differential equations of its perturbed motion. The perturbing effect of 9 planets was taken into account and the heliocentric coordinates from 1682 to 1986 were derived, to a required degree of accuracy, by a numerical integration of the differential equations of motion in the Sun's central gravity-field. Indirect planetary perturbations were also taken into account. The effect of the Earth-Moon system on the motion of the other planets is presented as a disturbing effect of a material point located in the Earth-Moon system barycenter and with a mass equal to the sum of their masses.

A rectangular equatorial coordinate system $O^S X^S Y^S Z^S$ is used to describe the motion of the comet. The origin of these coordinates is in the Sun's center of mass. The plane $X^S Y^S$ of the system coincides with the plane of the mean Earth's equator for the epoch 1950.0. The X^S-axis is directed toward the vernal equinox of the epoch, the Z^S-axis is aligned along the Earth's rotation axis toward its North Pole, and the Y^S-axis completes the right-handed, orthogonal system.

This paper presents the comet's equations of motion in the Encke form, that is, they describe an increment in acceleration. To improve the accuracy, relativistic corrections are introduced in the classical Newtonian equations. The corrections are based on the solution of the Schwartzschild equation for a spherically symmetric gravity field of general relativity theory. A standard coordinate system is used. The nongravitational accelerations in the right-hand sides of the differential equations are introduced by radial and transverse terms in the form suggested by Marsden (1974).

To improve speed, integration accuracy and a saving of computer memory volume, we modified Everhart's (1974) computation procedure for the method of numerical integration of common differential equations. The algorithm was realized in ASSEMBLER language by Savchenko (1982). The introduction of non-linear extrapolations for the divided differences made it possible to reduce the number of references to the right-hand sides of the differential equations. When using processed observations to improve the parameters of motion of celestial bodies, a number of state vector calculations are made. Therefore, in case of the developed algorithm, kinematic parameters are calculated by means of interpolation of the right-hand sides of the differential equations and then the state vectors are found with a high accuracy. Systematic errors in the integration of the equations of motion of Comet Halley and the nine planets were estimated by two ways: (i) comparison of the results obtained by integration forward-and-back of the initial point, and (ii) comparison of deviations from the reference orbit which had been calculated with the doubled number of nonzero digits. This comparison showed that a systematic error does not exceed 4×10^{-7} a.u.

The possibility of constructing a theory of motion depends to a great extent on the accuracy of the numerical values and on a correlation between the set of constants and the set of planetary coordinates. To develop this theory, we employed the astronomical constants, coordinates and velocities of the planets obtained by Oesterwinter and Cohen (1972) over the fifty-year interval of optical observations.

Comet Halley has an ancient history of observations. In 1682 the angular positions of the comet were obtained by means of a 7-foot sextant, with sufficiently high (at that time) accuracy. Struve and Bessel made a series of precise measurements during the apparition of 1835. Many angular optical observations from observatories equipped with powerful telescopes were obtained during the 1910 apparition. In our work we used all the unequally accurate observations of the comet made by different instruments and from different observatories. Astrometric measurements performed at various time moments often refer to different systems of reference, therefore they should be reduced to one and the same system of coordinates referred to a certain epoch. Strictly speaking, this requirement is not a necessity and one can work with rather different astrometric measurements but for convenience in our analysis all the observations made during 1759-1911 were reduced to the standard type $\alpha 50.0$, $\delta 50.0$. Optical observations of Comet Halley during 1682-1911 are presented by relative observations and observations of right ascension and declination referred to the mean equator and the equinox of 1950.0. The paper of Rosenberger (1831) deals with reference stars relative to which the cometary angular distances have been determined for 37 relative observations of Comet Halley made by Flamsteed in 1682. Rosenberger used 26 observations for which he had obtained a mean error in coincidence equal to $53.13''$. It should be noted that Brady and Carpenter (1971) and Yeomans (1977) used observations of 1682 which Halley had reduced to the form α, δ. The use of relative observations makes it possible to avoid errors in recalculating relative observations in order to obtain right ascensions and declinations and also to preserve the natural correlation of the observations.

The estimation accuracy of a least-squares solution depends on how observation weight characteristics were assigned. To analyze the observation accuracy for various apparitions, the observations were fitted locally. Table 1 lists the results. The obtained r.m.s. errors in σ were used for assigning weight to some observations while developing a theory. N is the number of observations, K is the number of observatories and the first and second lines refer to the right ascension and declination respectively.

Table 1.

17590122-17590306			18350821-18360517			19091009-19110524		
N	K	σ	N	K	σ	N	K	σ
143	7	26.4''	812	19	9.4''	2045	54	1.56''
120		28.6''	809		8.8''	2045		1.48''

Rectangular coordinates and velocities of the motion of the comet's mass center in the system of coordinates (X^S, Y^S, Z^S) referred to the time moment T_0 = 19110527.0 ET and coefficients A_1, A_2 were chosen as the parameters to be determined. The least-squares method, whose computational scheme is simplest, was used to determine the improved parameters. Derivatives of the right-hand sides of the differential equations of the comet's motion relative to the central body are calculated if there are 9 point perturbations.

Roemer (1961) disputed the presence of nongravitational perturbations. According to her opinion the discrepancies in the comet's orbital elements at different apparitions are explained by difficulties in the observations and in the studies of its motion, i.e., by the systematic shift of the optical center of the cometary nucleus from the gravitational center, the asymmetry of the comet's image near the Sun, the accumulation of errors in integration near the pericenter and in regions of close planetary approaches, the errors in approximation of the Earth-Moon mass center motion, and the inaccurate knowledge of planetary masses.

An approximation of the Earth-Moon motion during an interval equal to the period of the comet's motion provides an accuracy of $3 \cdot 10^{-6}$ a.u. that is sufficient for the aims of this paper.

The elimination of nongravitational accelerations from the equations of the comet's motion requires a correction to the perihelion passage time of four days. Besides, the adopted model of nongravitational forces agrees with the modern ideas about cometary physics.

The paper of Kustaanheimo and Lehti (1969) gives the formula and the value of the change in the sidereal period P of Comet Halley, obtained according to the general theory of relativity, relative to the period P_0 of the comet moving in Newton's field. The introduction of relativistic terms to our differential equations of the comet's motion leads to consistent results. The value P^{-1} $(P-P_0)$ is 0.0997 days. The allowance for the relativistic term in the differential equations of the comet's motion also makes it possible to decrease slightly a r.m.s. discrepancy in the right ascension and leads to a decrease in the parameter A_1.

The estimation accuracy of the determined solution parameters depends on how the weight characteristics of some observations were assigned. The condition of the comet's visibility during its apparition in 1910 allows the conclusion to be made that the rather high r.m.s. discrepancies then are caused by the difficulty in identification of the comet's mass center. A month after the pericenter passage Comet Halley was observed as a light spot with a diameter of 30 arcseconds without a central condensation. The shift of the optical center from the center of gravitation can lead to essential errors in improving kinematic parameters. While processing positional observations of the planets the correction associated with the phase effect is very important. We investigated the effect of this correction on the orbital accuracy of Comet Halley. As the reflection properties have not been studied well enough even for the atmospheres of the planets, we have adopted the simplest law for the light reflection - the law of mirror reflection. The coma size is assumed to be inversely proportional to the Comet's distance from the Sun.

The first line of Table 2 gives the results of processing observations in 1910 and the predicted time of the pericenter passage in 1986 with coefficients A_1, A_2 obtained by Savchenko (1982) from the observations of three apparitions. The second line gives the result for a similar set of observations but with reductions for a phase. The third line gives the result of the generalization of observations in 1909-1911 for which the correction of weights of some observations was made in accordance with phase corrections and a priori weight.

Table 2.

	T_r	A_1	A_2
1	198602 10.9673	0.1821	0.0157
2	198602 10.4422	--	--
3	198602 09.7805	--	--

The change curve of the absolute value of the right ascension deviation is represented in Fig. 7. This deviation is due to the optical center shift with respect to the comet's mass center. It is apparent that the adopted model of the optical center shift is in sufficient accordance with the observational data (Fig. 5).

While developing the theory, the weights of observations were assigned on the basis of two independent error sources. One of them is the fluctuation error caused by random errors. The second error is caused by the shift of the optical center. The determined values of the rectangular coordinates (a.u.), and velocities (a.u./100 days) at the moment of improving T_0 (equator and epoch of 1950.0) and the values of the coefficients of the non-gravitational accelerations (a.u./(10^4 days)^2) are listed in Table 3. Table 4 presents osculating elements obtained on the basis of the developed theory and referred to various time moments. The number of observations processed and the r.m.s. deviations characterizing the coincidence of the developed theory with the observations are given in Table 5. The results of fitting the observations are illustrated in Figures 1, 2, 3, 4, 5, 6.

Table 3.

X	-4.8031131546
Y	1.9592723576
Z	-0.84369384555
V_x	-0.72636019455
V_y	0.65724310917
V_z	-0.03913822058
A_1	0.18978
A_2	0.01588

Table 4.

T_{rp}	q	e	ω	Ω	i	T_{osc}
19860209.4696	0.5871023	0.9672708	111.8474	58.1456	162.2394	19860219
19100420.1783	0.5872044	0.9672982	111.7168	57.8455	162.2159	19100509
18351116.4393	0.5865597	0.9673883	110.6850	56.8014	162.2560	18351118
17590313.0125	0.5844623	0.9676814	110.6901	56.5284	162.3697	17590321
16820915.2830	0.5826139	0.9679250	109.2044	54.8497	162.2620	16820831
16071027.7630	0.5836320	0.9674914	107.5303	53.0511	162.8983	16071024

Table 5.

Observation type	Total number of observations	Number of processed observations	
$\alpha_{50.0}$	3000	2484	$7''.8$
$\delta_{50.0}$	2974	2492	$7''.3$
S	37	26	$34''.1$

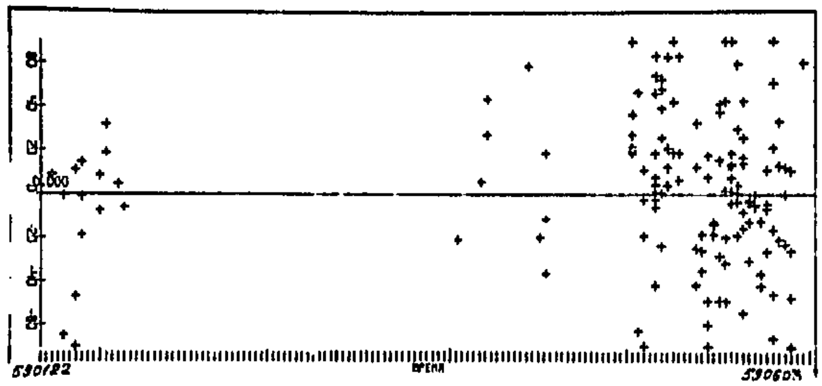

Fig. 1. Discrepancies in the right ascension data of 1759

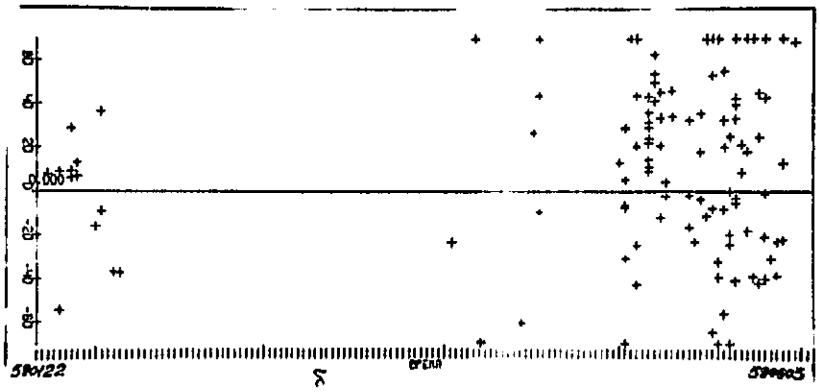

Fig. 2. Discrepancies in the declination data of 1759

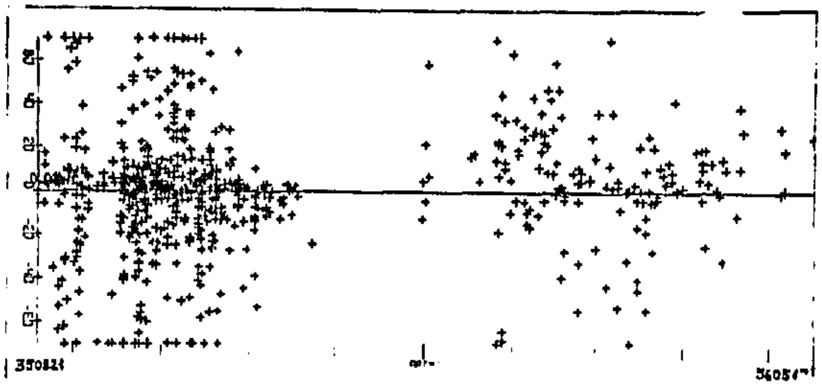

Fig. 3. Discrepancies in the right ascension data of 1835-1836

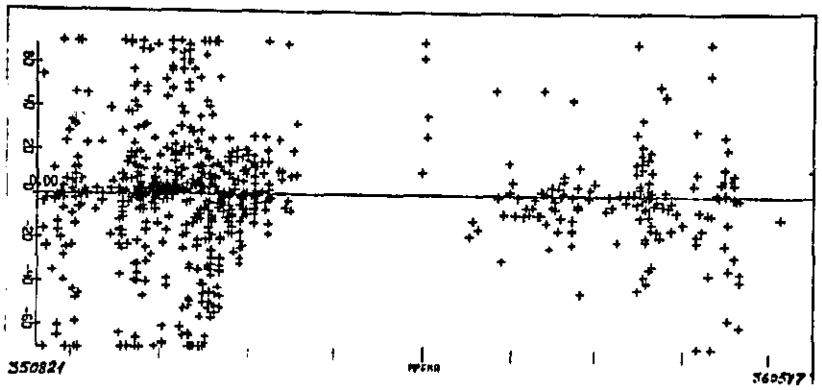

Fig. 4. Discrepancies in the declination data of 1835-1836

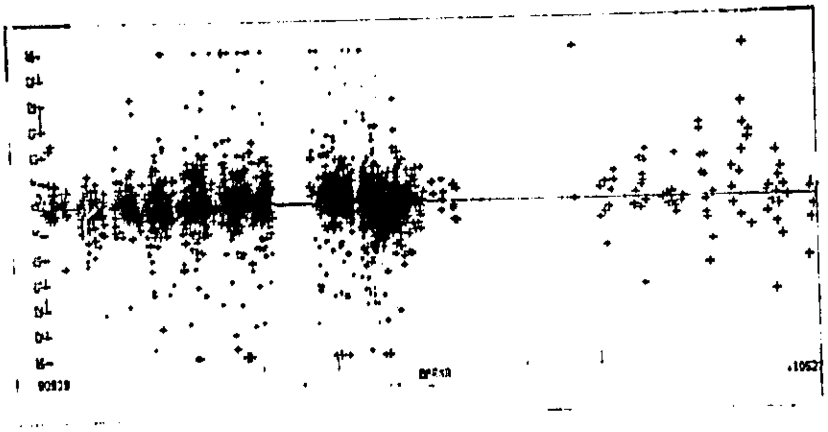

Fig. 5. Discrepancies in the right ascension data of 1909-1911

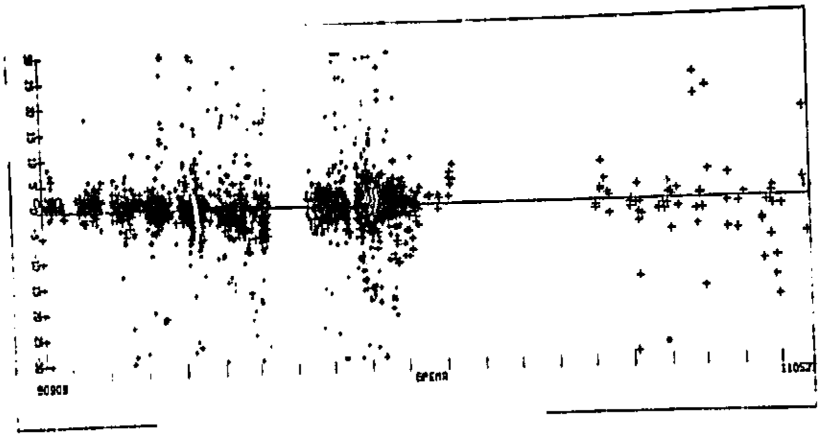

Fig. 6. Discrepancies in the declination data of 1909-1911

Fig. 7. Shift of the optical center

Comet Halley was recovered by Jewitt et al. (1982) by means of a 5.1-m telescope at Mount Palomar Observatory, at that time the comet was at the position:

1982 UT October 16.47569 $07^h\ 11^m\ 01^s.9 \pm 0.3$ $+09^\circ\ 33'03 \pm 5$

The comet's motion parameters obtained here make it possible to calculate discrepancies between the measured and estimated values and to control the accuracy in determining its orbital motion while predicting for seventy years ahead. According to the method discussed above the estimated geocentric parameters at the moment of the comet discovery were:

1982 UT October 16.47569 $07^h\ 11^m\ 01^s.92$ $+\ 09^\circ 33'04''.53$

Therefore, the prediction for 1982 gives good agreement in the theoretical and observational data. The deviations in the measured angles do not exceed 1.5", i.e., they are within the limits for the errors in the measurements. Similar discrepancies were obtained from observations from Kitt Peak Observatory and from the European Southern Observatory.

There are 82 Comet Halley observations over the span 1982 - to the beginning of 1984. The orbit obtained with the data over the span 1682-1984 slightly differs from the one which has parameters given in Table 4. The pericenter passage time is now 19860219.4727.

The procedure described above for the shifting of the optical center with respect to the comet's mass center gives hope that the maximum shift for the right ascension will be no worse than 0.6" in the middle of December 1985. That is why the accuracy of the cometary optical observations must be sufficiently high in late 1985 and early 1986.

REFERENCES

Brady, J.L. Carpenter, E. 1971. The orbit of Halley's Comet and the Apparition of 1986. Astron. J. 76(8), pp. 728-739.

Yeomans, D.K. 1977. Comet Halley - the orbital motion. Astron. J. 82(6), pp. 435-440.

Marsden, B.G. 1974. Comets. Ann. Rev. Astron. Astrophys. 12, pp. 1-21.

Everhart, E. 1974. Implicit Single-sequence methods for integrating orbits. Cel. Mech. 101(1), pp. 35-65.

Savchenko, V.V. 1982. The Numerical Integrating of Comet and Planetary Motion Equations by Everhart's Method. Preprint Inst. Appl. Mathem. the USSR Academy of Sciences. 161, p. 19.

Oesterwinter, C., Cohen, C.J. 1972. New orbital elements for Moon and Planets, Cel. Mech. 5(3), pp. 317-395.

Rosenberger, O.A. 1831. Elemente des Halley'shen Kometen bei seiner vorletzten Erscheinung im Jahre 1682, Astron. J. 9(196), pp. 53-68.

Roemer, E. 1961. Astrometric observations and orbits of comets. Astron. J. 66(8), pp. 368-371.

Kustaanheimo, P., Lehti, R. 1969. A new Astronomical Effect of the General Theory of Relativity: The Dilation of the Sidereal Period of Orbits with Great Eccentricity. Astron. J. 68(6), pp. 392-395.

Savchenko, V.V. 1982. Determination of the Orbital Elements for the Comet Halley. Kiev Komet Tsirk. 295.

Jewitt, D.C. et al. 1982. Recovery of Comet Halley. I.A.U. Announcement Card No. 3737, dated 1982 Oct. 21.

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THE WORK ON COMET HALLEY'S ORBIT AT ESOC

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ABSTRACT

The presently foreseen target for the GIOTTO spacecraft is a fly-by past the sunlit side of the nucleus of comet Halley with a distance at closest approach of 500 km. The predominant error source in the final navigation is due to uncertainties in the comet's ephemeris. Efforts are being undertaken at ESOC to improve the prediction of the comet's state at the time of encounter by GIOTTO. Some of the aspects involved in the problem are discussed here. They include ways to improve old observations by remeasurement or re-reduction and encouragement to observers to take fine quality astrometric observations in the future, especially at critical times. Also addressed are the difficulties in the mathematical modelling of the non-gravitational forces and possible offsets of the comet's centre-of-light from its centre-of-mass. The available estimation techniques are also examined including a rather novel one based upon selecting optimum observations.

INTRODUCTION

To satisfy the navigational requirements of the GIOTTO mission a general ephemeris of comet Halley is of limited use only. Much more important is a precise prediction of the comet's position, and to a lesser extent its velocity, during the brief four hours encounter period on the night between the 13th and 14th March 1986. The prediction of the comet's state will be based on fitting a trajectory to observations taken prior to encounter and extrapolating that trajectory to the encounter time. The accuracy of this extrapolation is critically dependent upon the quality of the most recent observations and the length of time between the last observations and the time of encounter. Hence ground-based astrometric observations in early March 1986 and pathfinder data from the VEGA spacecraft during the same time period are of upmost importance to ESOC (European Space Operations Centre) and the GIOTTO project.

The prediction accuracy is also very much dependent on how well a trajectory can be fitted to the available observations, i.e. the quality of the orbit determination. Comet Halley orbit determination has to cope with processing observations, the errors of which may be correlated as well as containing both random and systematic components. Moreover, it has to use models for the non-gravitational forces and possible displacement of the centre-of-light of a cometary image from the centre-of-mass (nucleus) whose adequacy, at best, is limited by the degree of knowledge of the physical and chemical processes occurring in the comet's environment and which cause these effects. Last, not least, the estimated orbit depends upon the solution technique used.

It is these aspects of the comet Halley orbit determination which are addressed in this paper. After describing the problems in more detail and methods to overcome them, some current orbit determination results are presented.

ASTROMETRIC OBSERVATIONS OF COMET HALLEY

Astrometric data of comet Halley are available only over a comparatively short arc of each orbital revolution centred roughly at perihelion. An apparently adequate orbit fit to data from two apparitions can be achieved using a purely gravitational force model. The resulting ephemeris, though, would not be acceptable since there is, for example, a secular increase in the orbital period of approximately four days which is explicable only by the action of non-gravitational forces. Thus non-gravitational forces must be introduced in order to fit an orbit through data from three apparitions and conversely, data from at least three apparitions must be used if the orbital parameters and coefficients of the non-gravitational forces are to be estimated.

Over intervals of 76 years, technological advances are reflected in the improvement in the accuracy of cometary astrometric observations. The average errors on the individual measurements (either right ascension or declination) for the four most recent apparitions of comet Halley are shown in Table 1 (Morley, Oct. 1983).

Table 1. Random Errors of Comet Halley Astrometric Observations

Apparition	Accuracy of Individual Measurements
1759	31".5
1835-36	5".5
1909-11	2".0
1982-84	1".0

The figures given apply only to the random components of the errors and exclude systematic errors or biases. Any realistic orbit determination must take into account the wide range of inherent accuracy in the observations. Thus, in a conventional weighted least squares approach, the measurements are weighted so that greater account is taken of the more recent ones. This weighting must be correctly applied otherwise the statistics, the measure of the accuracy of the estimated solution, will not be realistic. Furthermore, the accuracy estimates obtained using the least squares technique will be reasonable only when the observational errors are essentially random and uncorrelated. If this is not the case, then either an attempt must be made to model the biases or, better, to remove them from the original observations.

Observations from the 1909-11 apparition

There are literally hundreds of photographic plates still in existence from the previous apparition of comet Halley. Many of these plates are still in a sufficiently good condition and contain images of the comet which are suitable for remeasurement and re-reduction of the coordinates. The benefits to be expected are a reduction in both the systematic and random components of the observation errors due primarily to:

(i) better pinpointing of the centre-of-light of the image and a more accurate measurement of its plate coordinates and

(ii) more accurate measurement of the plate coordinates of the reference stars and a better determination of their (inertial) positions from modern star catalogues.

The process of remeasurement means that we can obtain astrometric data from the previous apparition which is almost as accurate as data from the present apparition. The qualifier reflects the degradation of the plates (e.g. movement of the emulsion) over the intervening 70+ years and the fact that some of the exposures were somewhat longer than the optimum for the most precise measurements.

Already eight plates taken at Heidelberg and four at Lowell have been remeasured. For two of the plates, comparison of the re-reduced positions with those originally published show differences in both right ascension and declination of between 2" and 3". Re-reduction of 31 Cordoba observations (Morley, Nov. 1983) using only a modern star catalogue, indicates a systematic error in right ascension of greater than 1" with individual errors of up to several arc seconds in both coordinates. Full remeasurement of the suitable Cordoba plates will be made in the near future.

For the purposes of contemporary orbit determination, a hundred remeasured observations, well spaced over the previous apparition, will be more useful than four of five times as many of the original observations.

Observations from the 1835-36 apparition

Since photographic plates were not available at this time, there are more limited possibilities to improve the astrometric data.

The quality of measurements taken 150 years ago was very much dependent on the skill of the individual observers. Some were very meticulous with the notes they made in their log books, recording not only auxiliary information like the sky conditions, how they took their measurements, the number of individual measurements per observation etc., but most importantly the reference stars used and the position of the comet relative to the reference stars. Bessel at Königsberg and Struve at Tartu are two such observers, whose superiority to others is also indicated by an analysis of the residuals of their observations (Morley, Oct. 1983).

Improvement of the 1835-36 observations is therefore being made by concentrating on a reduced set of observers and re-reducing the data using modern star catalogues. The analysis also includes using relatively recently determined and more accurate values for the constant of precession and the fictitious rotation of the equinox. The errors introduced by not using the most up-to-date values grow with the time difference from 1950.0 - the epoch to which all the observations are reduced. However, great care must be taken that the observations, the planetary ephemerides and the GIOTTO orbit all refer to the same reference system, namely that defined by FK4.

Observations from the present apparition

It is not our intention here to recommend how skilled astrometrists should take observations but rather to indicate which observations are most useful to the GIOTTO mission and some of the problems involved in taking them and using them for orbit determination purposes.

Since its recovery in October 1982, the difficulties with taking astrometric observations of comet Halley up to now have been due to the comet's faintness. Even the latest observation from 4th March 1984 has a brightness estimate of the order of 23 for the nuclear magnitude. Nevertheless, only [illegible] of the 44 observations have had to be rejected for orbit determination purposes because their associated residuals are substantially greater than the mean scatter. (They include the 5 Mt. Palomar recovery observations). In the future, the difficulties associated with faintness will give way to difficulties arising from pinpointing a diffuse object which is becoming increasingly more active.

For the targeting of the GIOTTO spacecraft, the most critical observations are those taken in the first ten weeks of 1986, and especially in late February and early March, and those taken around the end of November 1985. This last date corresponds to when the comet makes its closest pre-perihelion approach to the earth. Cometary position measurements made at close geocentric distances, when the comet's apparent motion is large, are the most powerful observations for ephemeris improvement. In particular, these observations reduce the comet's position error component along its track.

Accurate astrometric observations in early 1986 are difficult for two reasons. First, perihelion passage occurs on 9th February 1986 so the period coincides with the time when the comet is expected to be most active. The danger is then a consequent orbit fit to centre-of-light measurements which are systematically offset from the nucleus and which could lead to a disastrous fly-by of GIOTTO past the dark side of the nucleus. Second, superior conjunction occurs three days earlier on 6th February 1986. On and around this date no ground-based observations will be possible. The duration of the blind period is problematic but will probably be at least three weeks (Morley, 1982). Naturally, we are concerned that it should be as short as possible. The observers, though, will have to cope with the dual problems of trying to observe close to the horizon in a relatively bright sky. It will also be necessary to reduce observations taken in late February and early March 1986 rather quickly if they are to be useful for final targeting of GIOTTO.

VEGA Pathfinder observations

The comet orbit will mainly be determined from astrometric or angular data. Radar observations could provide valuable information on the position of the nucleus. Angular data will also be collected on board the Russian spacecraft VEGA 1 and 2 that encounter P/Halley between 6 and 9 days prior to GIOTTO. Mission analysis studies revealed that those 'pathfinder data' may allow much better localisation of the nucleus than from ground based observations alone. The VEGA spacecraft will fly by the nucleus at about 10 000 km and we notice that even the envisaged maximum angular errors of 10 arcmin in the pathfinder data will not contribute more than $10^4 (0.01745) \frac{600}{3600} = 30$ km to the uncertainty in the nucleus position. This may be compared with a ground based observation of 1" accuracy which at 1 AU (approximately the GIOTTO fly-by distance) is equivalent to 725 km. ESOC will incorporate the pathfinder data into the orbit determination process.

Useful VEGA data will only be collected during, at most, 4 hours at each fly-by. It is obvious that these data will provide very local information on the comet position. This information need not necessarily confirm the long arc orbit determination results from astrometric data. It is an important task of the orbit determination at ESOC to analyse the influence of the different error sources in either the VEGA data, the ground-based observations or even in the force model on the results. Differences must be explainable in order to gain confidence in the solution.

THE NON-GRAVITATIONAL FORCE MODEL

The gravitational forces influencing the motion of Halley's comet can be very accurately modelled. The same cannot be said for the non-gravitational forces and for modelling possible offsets of the centre-of-light from the centre-of-mass.

The most widely used non-gravitational force model is that due to Marsden et.al. 1973. This is supposedly based on the sublimation of water-ice, and the forces vary as a rather complex function of heliocentric distance and are zero at distances greater than 2.8 AU. More recently other models have been proposed, for example by Rickman and Froeschlé 1982, in which the forces follow different functions of heliocentric distance, are non-zero at much greater distances than 2.8 AU and are not necessarily assumed to be symmetric about perihelion. To test the suitability of candidate models and to find the best requires a number of considerations to be taken into account:

(i) As far as possible, known or suspected systematic errors in the observations should first be removed.

(ii) If the orbit is determined using weighted least squares, then deficiencies in the non-gravitational force model will not only lead to a biased solution but will also lead to optimistic error statistics. As already discussed in the context of the observations, the ephemeris uncertainty or covariance matrix reflects only the random errors of the observations.

(iii) The introduction of additional uncertain parameters into the weighted least squares process always leads to a better fit of the solution to the data as measured by the residuals' statistics. The uncertain parameters must be part of a model which is related to the (assumed) physical reality and for a good model should lead to significantly better residuals. (Such was the case of course with the original introduction of a non-gravitational force model into cometary orbit determination).

(iv) The estimated values of coefficients of non-gravitational forces may change when a model for centre-of-light/centre-of-mass offsets is also used.

(v) As we have already pointed out, data from three apparitions are needed to estimate the coefficients and they are therefore mean values over at least two orbital revolutions.

An appropriate test for a good model is consistency. The different estimates for the non-gravitational force model coefficients using data from different and overlapping sets of apparitions should be consistent with their associated error estimates. The results of such a test for the model of Marsden et.al. are shown in table 2.

Table 2. Estimates of the coefficients of the non-gravitational forces

Observations	Radial Force Coefficient A_1	Tangential Force Coefficient A_2
1759-1911	0.1140×10^{-8} AU/day^2	0.0157×10^{-8} AU/day^2
1759-1984	-0.0135	0.0156
1835-1984	0.0838	0.0155
	(± 0.021, 1σ)	(± 0.000012, 1σ)

The estimates for A_2 appear quite consistent, with the possibility of a slight decrease over time. The same is not true for the estimates of A_1, and certainly from physical considerations a negative value is unlikely. It may be noted also from the error estimates how difficult it is to observe A_1 (because it has no significant secular influence on the orbit) compared with A_2 (which causes the secular increase in the orbit period). Also apparent, is that differences between the estimates are rather larger than would be expected from the quoted uncertainties.

Better knowledge of the nucleus spin direction, its rotation period and thermal characteristics, in conjunction with the apparently good estimate of A_2, would help to fix the value of A_1. Since the spin axis is currently thought to lie about 45° from the orbit plane (Sekanina and Larsen, 1984), there should also be an out-of-plane non-gravitational force, with associated coefficient A_3. Because of its periodic nature, with frequency parameter the true anomaly, this coefficient is also difficult to observe. Nevertheless it should be included otherwise the position error component normal to the orbit plane will be unduly optimistic.

A reliable estimate for A_2 allows the long term evolution of the comet's motion to be predicted with some confidence. However, it represents the integrated effects of the tangential forces over the whole of an apparition. A good estimate is not the same as saying that we know how the non-gravitational forces act throughout the apparition, even when stochastic or transitory effects are left out of consideration. A good test for this aspect is the absence of systematic trends in the observation residuals. Unfortunately, this is not the case for comet Halley. In the month centred around the close approach to the earth in May 1910, in particular, there is a distinct bias of between 2" and 3" in the right ascension residuals. Nor can this trend be explained by a relatively simple observation bias model.

THE CENTRE-OF-LIGHT/CENTRE-OF-MASS OFFSET MODEL

A realistic observation bias model should take into account more parameters than the comet's activity. For example, it is reasonable to suppose that any bias would also be dependent upon the observation exposure time and the type of filter used. Even if we assume that any bias lies along the sun-comet vector, the difficulty lies with forming a functional relationship between the bias and the various parameters having an influence.

Undoubtedly, the best way around the problem is to rely on observations with the minimum exposure time. The images of the bright comet, which are best for astrometric purposes, are those which show, at most, the inner coma.

Fortunately, the sun-comet-earth geometry in early 1986 is relatively favourable, in that any assumed bias along the sun-comet vector will be significantly foreshortened when seen from the earth. Nevertheless, we still have to rely to a certain extent on some earlier observations which are in error due to the centre-of-light offset. Observations taken at close approaches to the earth are particularly valuable for their information content but are also among the most likely to be affected by observation biases.

Recently, Landgraf 1984, has proposed a technique whereby observations of the bright comet are processed in a different way in the orbit determination. The method relies on using only that part of the information content within the observations which applies to the direction perpendicular to the sun-comet line. The residuals can later be examined to see whether there is any apparent observation bias. The technique implicitly assumes the direction of any presumed bias and may lead to information being lost from some astrometric data which in reality are very accurate. We at ESOC have not yet studied this proposal in any detail.

TECHNIQUES USING THE METHOD OF WEIGHTED LEAST SQUARES

A routine orbit determination involves augmenting the state vector so that model parameters are estimated simultaneously with the comet's orbit and data from a number of apparitions are processed. This is the so-called long-arc orbit determination. An alternative is the short-arc solution where recognition is made of the possibility that the mathematical force model is sufficiently accurate only over a limited time span. A typical orbit determination for the GIOTTO encounter might entail first a long-arc determination using data up to 1985 and then using the solution and a degraded covariance matrix (multiplying the elements by a factor greater than 1 and possibly removing some correlations) as a priori information for a short-arc determination using the most recent data. This has the effect of weighting the solution more in favour of the most recent observations. If the assumptions on the deficiencies of the model are true, it should also lead to a better estimate of the comet's position in 1986. The error estimates would be higher, though probably more realistic, than if all the data had been processed in a long-arc determination.

An alternative technique is to treat some of the uncertain parameters as consider parameters, in which case they are not estimated. The rationalisations of this assumption are that such parameters may be difficult to observe, i.e. not estimable from the data or not separable from other parameters, or that estimating them may lead to an overly-optimistic covariance matrix. An important by-product of the consider covariance is the sensitivity matrix which relates errors in the consider parameters to errors in the estimates of the solve-for parameters. The ESOC Halley orbit determination program can treat any of the parameters of candidate models of the non-gravitational forces or observation biases as being either solve-for or consider parameters.

OPTIMUM OBSERVATION STRATEGY

The GIOTTO mission requires a minimum target error. This error is a function of the comet trajectory determination error, which is in turn a function of the observation errors. There is some evidence that the observation errors in particular in the 'old' observations are not uncorrelated and that they contain systematic components (clock and star catalog biases, offset between centre-of-light and centre-of-gravity).

It has been normal practice to determine the 'best' trajectory from a Gauss' least-squares fit of the observations. We can, however, show by means of a very simple example that such a trajectory does not necessarily provide smallest target errors. We can furthermore demonstrate that other trajectory determination criteria better take into account the a priori information on the observation errors and that they better reflect our requirements on the target accuracy.

We analyse the following 2-dimensional example:
Let us assume that we try to determine a linear trajectory $y(t)=at+b$ from N observations $y_i=y(ti)$, $i=1...N$ and that the true trajectory is the x-axis, i.e. $y(t)=0$. Hence the error-free observations would be $y_i=0$. The target is the value of $y(t)$ at $T > t_N$, i.e. our target error will be $\Delta\tau = y(t) = aT+b$.

All a priori information we have on the observation are upper limits $\bar{y}_i$ for the observation errors, i.e.

$$|y_i| < \bar{y}_i, \; i = 1 \ldots N.$$

This assumption is similar to a case where all observation errors are fully correlated. The $\bar{y}_i$ might have different values (old data versus new data, star-like cometary images versus coma surrounded nuclei).

Figure 1 shows a typical case with 6 observations together with a straight line or trajectory $y_1(t)$ that is a least squares fit of the data. Each observation error assumes one of its extreme values $\pm y_i$. The corresponding target error is $\Delta\tau_1$.

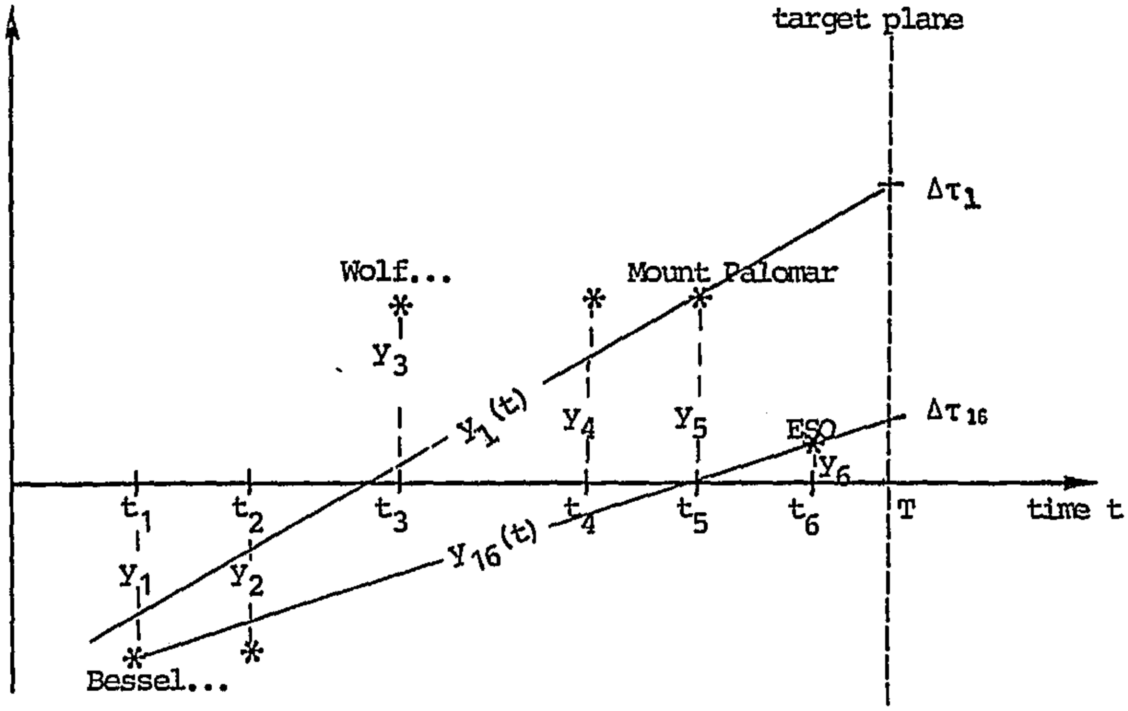

Fig. 1: Least squares fits

We next study our trajectory determination problem from a different point of view. We are interested in a trajectory providing a minimum target error. Figure 2 shows some trajectories $\overline{y_{ik}}(t)$ determined from only two observations $y_i \neq y_k$. The sign of the maximum observation errors is selected such that the target errors $\overline{\Delta\tau}_{ik}$ assume their extreme values

$$\overline{\Delta\tau_{ik}} = \max_{|y_i| < \bar{y}_i \, |y_k| < \bar{y}_k} |\Delta\tau \; (y_{ik}(t))|$$

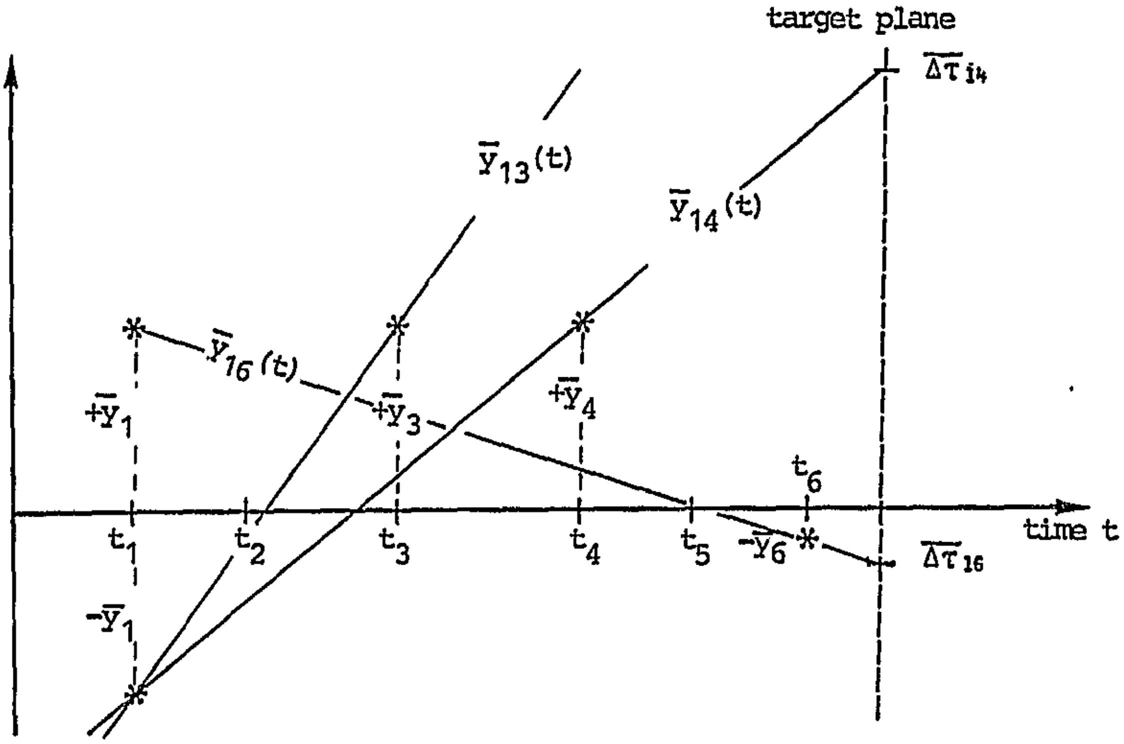

Fig. 2: Worst case target error for trajectories determined from 2 Observations

It is interesting to notice that even some extreme target errors of these worst case two-point fits $y_{ik}(t)$ like $\delta\tau_{16}$ are smaller than the error $\Delta\tau_1$ of the least squares fit $y_1(t)$. Furthermore $y_{16}(t)$ (see figure 1) i.e. the fit through two real observations is closer to the best solution $y(t)=0$ than $y_1(t)$.

In our case a least square fit does neither correctly take into consideration the a priori information on the observation errors nor does it give the smallest target error.

We also observe in figure 2 that

$$\overline{\Delta\tau_{16}} = \underset{i \neq k}{\mathrm{Min}} \quad \underset{|y_i| < \bar{y}_i \, |y_k| < \bar{y}_k}{\mathrm{Max}} \quad |\Delta\tau_{ik}(Y_{ik}(t))|$$

One can in fact replace the least square criterion by this condition in the trajectory determination process. The resulting rather unconventional solution methods have been developed over the last twenty years in the USSR and are widely used at the Space Research Institute of the USSR's Academy of Sciences (IKI) by the school of Prof. Elyasberg. One can rather easily incorporate a large variety of complex a priori information on the observation errors in these methods. They normally lead to the requirement to fit a trajectory through a small but optimally selected subset of observations, as was the case in the above 2-dim. example. By means of that technique one can determine 'guaranteed upper limits' of the target errors. For details we refer to the relevant literature, in particular to Elyasberg et al., 1980, 84.

CURRENT RESULTS

Based on the same set of observations, the same observation weighting and the same force model (due to Marsden et.al. 1973) and with no observation bias model, table 3 shows the latest Halley orbit determination results of JPL and ESOC. Both results were obtained using the method of weighted least squares but with quite different software. The JPL results are Yeomans' orbit no. 12. The similarity of the results gives us confidence that the software is essentially correct.

Table 3. Comparison of Latest Ephemerides from JPL and ESOC

No. of observations : 663
Observations span : 1835 to 1984 Mar. 4
RMS residual : 2.95" (JPL), 2.96" (ESOC)
Epoch : 1986 Feb. 19.0 (ET)
Reference system : mean equator and ecliptic of 1950.0

	JPL	ESOC
Time of perihelion (ET) :	1986 Feb. 9.44532	1986 Feb. 9.44493*
Perihelion distance (AU) :	.5871023	.5871023
Eccentricity :	.9672749	.9672748
Argument of perihelion (deg) :	111.84692	111.84693
Longitude of ascending node (deg) :	58.14415	58.14415
Inclination (deg) :	162.23932	162.23932
A_1 ($\times 10^{-8}$ AU/day^2) :	0.0853	0.0838
A_2 ($\times 10^{-8}$ AU/day^2) :	0.0155	0.0155

* Difference in predicted time of perihelion passage < 34 seconds.

Table 4 shows the predicted position of the comet at a time on March 13th 1986 within a day of the encounter by GIOTTO. The values in the left-hand column are derived from the same run as the results of table 3. The results in the right-hand column were obtained from a similar run with data from the 1759 apparition additionally used.

Table 4. Predicted position of comet Halley on 1986/3/13 16:11:58.3

Observation span	1835-1984	1σ uncertainty	1759-1984	1σ uncertainty
right ascension:	$20^h 1^m 14^s.22$	21".2	$20^h 1^m 19^s.92$	8".2
declination:	-21°51'5".6	11".0	-21°50'21".5	4".3
geocentric distance:	0.9703501AU	.0000518AU	0.9705560AU	.0000204AU

Future observations will reduce the uncertainties in the predictions. The important point to notice is that the differences between the estimates of the right ascension, declination and geocentric distance, 85".5, 44".1 and 0.0002059 AU respectively are significantly greater than would be expected from the error estimates. This serves to emphasise the problems of modelling and systematic errors which have already been mentioned.

CONCLUSIONS

Because the navigational demands of the GIOTTO mission are so stringent, the GIOTTO project requires an ephemeris for Halley's comet which is considerably more accurate than that needed by any other Halley mission or ground-based observer.

The Vega pathfinder data will be the best available for pinpointing the comet at the time of encounter. However, up until a few days before encounter we will have to rely on predictions based only on ground-based data. Furthermore, we must be prepared for the possibility that the Vega data is not received or that it is inconsistent with the other astrometric data. Both contingencies mean it is essential to be able to determine the best possible ephemeris using only ground-based data.

This paper has shown some of the aspects of Halley ephemeris determination which not only could be improved, but must be improved if these objectives are to be met. Within this context the quality of the astrometric observations taken during the next 21 months plays a crucial role and especially those taken in the period immediately before encounter.

REFERENCES

Elyasberg P.E., Bakhshiyan B.TS., Nazirov R.R. 1980. Definition and correction of motion (Nauka, Moscow) (in Russian).

Elyasberg P.E., Sukhanov A.A., Morley T., Hechler F. 1984. Orbit determination for Comet Halley by means of optimally selected observations. ESA Journal, Vol. 8.

Landgraf W. Private communication.

Marsden B.G., Sekanina Z., Yeomans D.K. 1973. Comets and non-gravitational forces. Astronomical Journal 78:2, pp. 211-25.

Morley T.A. December 1982. Comet Halley station predictions and auxiliary software. GIOTTO Study Note no. 36, OAD ESOC.

Morley T.A. October 1983. Analysis of the observations' residuals of Comet Halley. GIOTTO Study Note no. 45, OAD ESOC.

Morley T.A. November 1983. Re-evaluation of the observations of Comet Halley from Cordoba in 1909 and 1910 based upon improved positions of the reference stars. GIOTTO Study Note no. 46, OAD ESOC.

Rickman H., Froeschlé C. 1982. Model calculations of non-gravitational effects on Comet P/Halley. Proceedings of the International Conference on Cometary Exploration (Budapest, Hungary), III pp. 109-126.

Sekanina Z., Larson S.M. 1984. Coma Morphology and dust-emission pattern of periodic Comet Halley. II Nucleus spin vector and modelling of major dust features in 1910. Submitted to Astronomical Journal.

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ON THE ORBIT IMPROVEMENT RESULTS OBTAINED BY REFERRING OLD COMETARY OBSERVATIONS TO THE SAO STAR CATALOG

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ABSTRACT

An algorithm is presented for the automatic reduction to the SAO Star Catalog of old micrometer cometary observations of the type "comet minus star". Results of a numerical test are presented showing the distinct influence of such a reduction on orbit determination results.

INTRODUCTION

Our many years of experience in the determination of orbits shows that the elaboration of the observational material is very important for obtaining trustworthy results. Among the many effects which have to be taken into consideration during the data reduction process, there is the difficult problem of referring old observations to one star catalogue. We made an attempt to solve the problem using the SAO Star Catalog.

Reduction of old micrometer cometary observations to the SAO Star Catalog is possible when the angular distance ☄-✳ between the positions of the observed comet and that of the reference star is given by an observer as an offset in the right ascension $\Delta\alpha$ and declination $\Delta\delta$. Although observers often indicated the positions or numbers of their star catalog comparison stars, there is still the problem of locating these positions in the SAO Star Catalog. If thousands of observations are to be reduced, it is desirable to automate the process by using a computer and the SAO Star Catalog recorded on a magnetic tape. In this regard, we developed and tested, in practice, the algorithm described below.

ALGORITHM OF REDUCTION

As input data we have:

- orbital elements of the comet which well represent all the observations before reducing them to the SAO Star Catalog,
- values of apparent differences $(☄-✳)_{\mathrm{app}}$ for the moment of observation in right ascension and declination,
- positions and proper motion values for stars in the SAO Star Catalog (referred to the epoch 1950.0).

From the orbital elements of the comet we compute the ephemeris positions for the moments of observations $☄_{1950.0}$. If we assume

$$(☄-✳)_{\mathrm{app}} \cong (☄-✳)_{1950.0}$$

we find that a hypothetical position of the comparison star used by an observer to make the measurement is

$$✳^{\mathrm{hyp}}_{1950.0} = ☄_{1950.0} - (☄-✳)_{1950.0} .$$

Now we find the true position of the Star $\ast^{SAO}_{1950.0}$ in the SAO Catalog and we take into account the proper motion of the star, the corrections for precession, nutation and stellar aberration (Bielicki and Ziolkowski 1976) to obtain the apparent position of the star $\ast^{SAO}_{app}$. Hence we have the corrected position of the comet

$$\text{☄}_{app} = \ast^{SAO}_{app} + (\text{☄} - \ast)_{app}.$$

The main problem of this algorithm is an identification of the SAO Catalog star position according to the calculated hypothetical position $\ast^{hyp}_{1950.0}$. We compare $\ast^{hyp}_{1950}$ with all the star positions in the SAO Catalog within an area of radius ρ around $\ast^{hyp}_{1950.0}$ to choose the nearest SAO star to the hypothetical one in the area (the influence of stellar proper motions in the interval between the moment of observation and the epoch of the SAO Catalog must be taken into account when determining the positions of the SAO Catalog stars). We must use, of course, an appropriate radius ρ of this area. If ρ is too small we could find no star in the SAO Catalog neighboring the hypothetical star. On the other hand, if ρ is too large there is a danger of accepting a false star since the SAO Catalog does not contain positions for all stars on the sky.

The optimum value of the radius ρ can be deduced from the analysis of factors influencing the dispersion of the hypothetical position of the searched star $\sigma_{\ast\,hyp}$. We can write the following relationship

$$\sigma^2_{\ast\,hyp} = \sigma^2_{\text{☄}\,eph} + \sigma^2_{\text{☄}\,obs} + \sigma^2_{\ast\,SAO}$$

where $\sigma_{\text{☄}\,eph}$ is the dispersion of the ephemeris position of the comet calculated from the orbital elements, $\sigma_{\text{☄}\,obs}$ is the dispersion of the comet's observed position expressed by the mean residual of the set of observations, $\sigma_{\ast\,SAO}$ is the dispersion of the stellar positions in the SAO Catalog; we have

$$\sigma^2_{\text{☄}\,eph} = \frac{m}{N}\,\sigma^2_{\text{☄}\,obs}$$

where m is the number of parameters determined in the process of orbit improvement from N observational equations. According to the results of Bielicki (1972), concerning the objective selection of observations, we can find the factor K(N) which allows us to obtain the radius

$$\rho = K(N)\ \sigma_{*\mathrm{hyp}}.$$

NUMERICAL TEST

To test the above algorithm, and its influence on the results of orbit determination, we used observations of the long-period comet Daniel 1907 IV ($q = 0.51$ AU, $e = 0.9971$, $i = 8^{\circ}.96$). The comet was observed during one year during which 875 observations were made. We used only 245 observations covering a six-week arc of the orbit and used them to improve the orbital elements. We could verify the goodness of the improved orbit by computing the residuals (O-C) for observations made at the end of the observational interval in 1908. We made two orbit determination solutions applying the selection and weighting of observations and including other subtle effects in the process of orbit improvement (Sitarski 1983), and we obtained the following representation of the observations in 1908 as demonstrated by their mean residuals μ:

(a) $\mu_{1908} = 250''$ when we improved the orbit using 245 original observations,

(b) $\mu_{1908} = 70''$ when we improved the orbit using 245 observations among which 166 were processed according to the above algorithm.

It is evident that the correction of 68% of the observations using the SAO Star Catalog allowed a better determination of the orbital elements from the same observational material. It is worth noting that in case (b) four observations which in case (a) were rejected by a selection criterion as erroneous, were corrected during the reduction to the SAO Star Catalog and were included in the final orbit improvement.

Using the same data, we examined the method for the determination of the optimum value of the radius ρ. We changed ρ from $3''$ to $60''$ in five steps and we found that the number of corrected observations changed from 54 to 170. It turned out that the best fit to the observations in 1908 was obtained for $\rho = 18''$ when just 166 observations were corrected. This is in good agreement with the theoretical value of that radius $\rho = 15''.4$.

CONCLUSION

The described method for processing cometary observations was used to compile the Catalogue of Orbits of One-apparition Comets being prepared in Warsaw. It seems that this method can also be useful when improving the orbit of Comet Halley since almost all the observations of the comet in 1835-36 and in 1909-11 are published in the form of differences ☄ − ✱. We have just collected the observations of Halley's Comet and we will improve the orbit after reducing these observations using the SAO Star Catalog. The first attempt of applying the algorithm presented in this paper showed that among the 2123 observations of 1909-10 treated with processing, 1346 were reduced to the SAO Star Catalog.

The authors are indebted to Mrs. Wanda Borodziewicz for preparing the computer routines and performing the computations.

REFERENCES

Bielicki, M. 1972. The problem of elaboration and classification of observational material for one-apparition comets. in *The Motion, Evolution of Orbits, and Origin of Comets* eds. G.A. Chebotarev, E.I. Kazimirchak-Polonskaya and B.G. Marsden, D. Reidel (Dordrecht), pp. 112-117.

Bielicki, M. and Ziolkowski, K. 1976. Data processing for the comparison of the theory with the observations in comet motion. *Acta Astronomica*. Vol. 26, pp. 371-386.

Sitarski, G. 1983. Subtle effects in the investigations of motion of comets and minor planets. In *Asteroids, Comets, Meteors*. Eds. C.-I. Lagerkvist and H. Rickman (Uppsala: Uppsala University), pp. 167-170.

ASTROMETRIC NEEDS FOR THE ISEE-3/ICE MISSION TO COMET GIACOBINI-ZINNER

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ABSTRACT

The Third International Sun-Earth Explorer satellite (ISEE-3) was rechristened International Cometary Explorer (ICE) when the spacecraft left the Earth-Moon system after a close Lunar flyby on 1983 December 22. On 1985 September 11, ICE will pass through the inner parts of the tail of Comet Giacobini-Zinner to obtain the first in-situ measurements of any comet. Since the spacecraft has no cameras, its trajectory will be determined only from radio tracking. Astrometric updates of Comet Giacobini-Zinner will be critical for the final targeting of the spacecraft to achieve a successful encounter. ICE's flyby of Comet Giacobini-Zinner will provide valuable experience for the astrometry needed to target other spacecraft to encounter Halley's Comet six months later.

INTRODUCTION

ISEE-3 was launched on 1978 August 12 and placed into a "halo" orbit about the L_1 libration point between the Earth and the Sun 0.01 astronomical units from the Earth on 1978 November 21 (Farquhar _et al_., 1979). During ISEE-3's 4-year mission, the spacecraft measured the particles and magnetic fields of the Solar wind at its vantage point five times the Lunar distance towards the Sun, before there was any substantial interaction with the Earth's magnetosphere. The baseline Solar wind input to the Geomagnetic environment was very effectively monitored by ISEE-3.

ISEE-3 carried 89 kilograms of hydrazine fuel at launch, giving it a total ΔV capability of about 430 meters/second. This large fuel supply might have been needed to correct transfer trajectory errors and for halo orbit insertion and stationkeeping. Fortunately, the launch and transfer trajectory were very close to nominal, and the fuel costs needed to achieve and maintain the unstable halo orbit were less than expected. At the end of its design mission, ISEE-3 still had a ΔV capability of about 300 meters/second. In early 1982, project scientists approved an extended-mission phase to leave the halo orbit and use a new double-lunar swingby technique (Farquhar and Dunham, 1981) to explore distant parts of the Geomagnetic tail. The small maneuver to leave the halo orbit was executed on 1982 June 4. Later that year, Robert Farquhar and other mission analysts at Goddard Space Flight Center and at CSC (hereafter called "we") showed that

ISEE-3 could be sent to Comet Giacobini-Zinner after spending several months in the Geomagnetic tail. NASA approved plans to include the comet option in the extended mission in August of 1982. The exploration of the Geomagnetic tail, involving five Lunar swingbys and several propulsive maneuvers, proceeded as planned during 1983. ISEE-3's extended mission will be documented elsewhere (Farquhar et al., 1984).

HELIOCENTRIC ORBIT OPTIMIZATION AND TARGETING

ICE has ultimately been targeted to intercept Comet Giacobini-Zinner since late 1982. Astrometric observations for updating the comet target conditions have been, and will increasingly become, important just before major spacecraft maneuvers. The times of these maneuvers are chosen to minimize ΔV costs within mission and spacecraft constaints as discussed below. The quality of the cometary orbit determination derived from possible astrometric observations has also been considered in propulsive maneuver planning. The past maneuver and orbit determination history of the spacecraft give us some insight into the accuracies involved. This information combined with models of the comet structures and desired target conditions allow us to estimate the astrometric needs of the mission.

Maneuver Optimization

Last year while ISEE-3 was exploring the Geomagnetic tail, the most recent definite observations of Comet Giacobini-Zinner were those made near its last perihelion in 1979. Minimization of the heliocentric ΔV needed to encounter the comet depended on precise targeting for the December 22nd Lunar swingby, which boosted the spacecraft's velocity well above the Earth-escape value. We were concerned about the accuracy of the comet target, since the non-gravitational forces on Giacobini-Zinner have varied, even changing signs, depending on the apparitions used for the orbit determination (Marsden, 1982). When ICE started its heliocentric cruise phase, it still had about 230 meters/second ΔV capacity, enough to encounter the comet even if the predicted perihelion time were off by a large fraction of a day.

We were not able to find Lunar swingby parameters which would allow us to reach the predicted position of the comet with no maneuvers during the heliocentric cruise phase. Figure 1 shows the ΔV components needed to intercept Comet Giacobini-Zinner according to an optimized trajectory computed early in 1983. Various mission and spacecraft hardware constraints require that the ΔV be applied as two separate components, one in the ecliptic plane and the other perpendicular to it. Performing the maneuver early is not advantageous. It is better to wait until 1985 to allow more time for observations and orbit improvement.

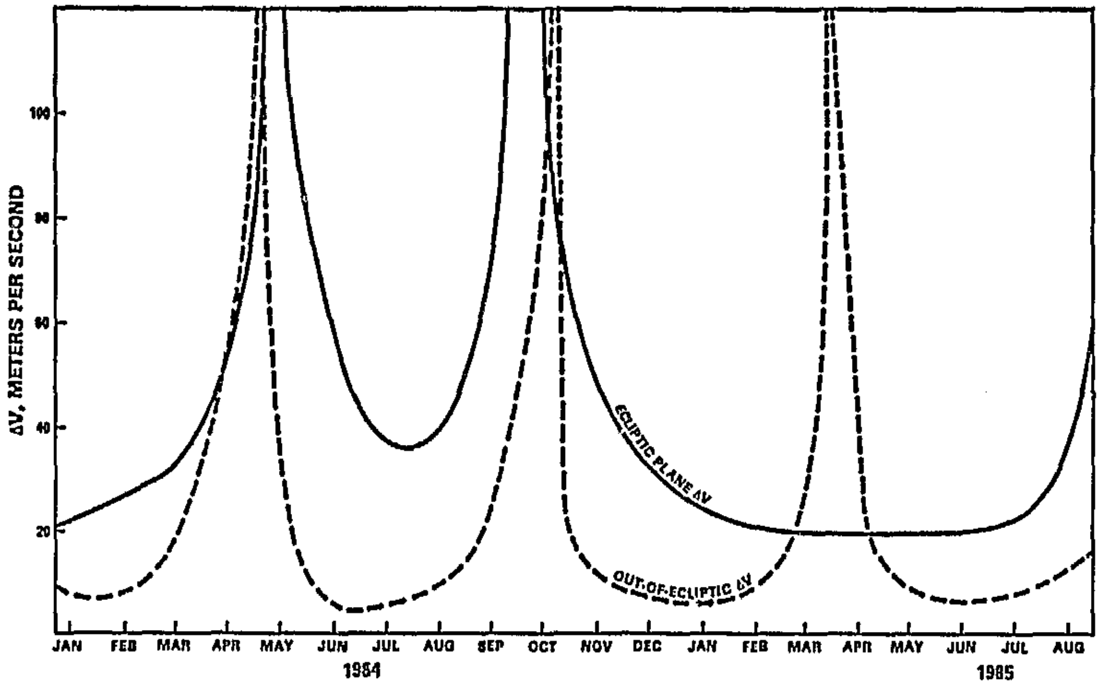

Fig. 1. ΔV components needed to intercept Comet Giacobini-Zinner computed before the final Lunar swingby

ICE's velocity vector relative to Giacobini-Zinner will be only 12 degrees from the ecliptic pole. Hence, the time of encounter (or a correction to the time of the comet's perihelion) can be varied by changing the heliocentric inclination of ICE's orbit with an out-of-ecliptic ΔV. Conversely, if we do not care when ICE encounters the comet, no out-of-ecliptic ΔV is needed. However, ICE's relatively large ΔV capacity allows us to select the encounter time. We have chosen 11:00 G.M.T., when ICE will be virtually overhead at Arecibo, Puerto Rico, and also well-placed for coverage by Jet Propulsion Laboratory's Deep Space Net antennas in Spain and California. Also at this time, Comet Giacobini-Zinner will be high in a dark pre-dawn sky as seen from major observatories in the southwestern U.S.A.

The out-of-ecliptic ΔV is pointed northward if the maneuver is performed around June, and southward if done near the beginning of the year. Since the southward-thrusting jets on ICE are canted to prevent plume impingement, their use is discouraged to avoid penalty factors. These jets have never been used for a large maneuver, so they are also poorly calibrated.

Recovery. Comet Giacobini-Zinner was recovered at Kitt Peak National Observatory on 1984 April 3; some earlier images were subsequently recognized (Djorgovski et al., 1984). Fortunately, Donald Yeomans' update of the orbit using the new data agreed with his previous orbit being used for our targeting to within 0.1 day for the time of perihelion passage in 1985. The 1984 observations are the most distant ones ever obtained for a short-period comet and should be useful for testing models for non-gravitational forces.

ICE Maneuver Plans. Figure 2 shows the optimization of the comet targeting maneuver using ICE's current trajectory and Yeoman's orbit for Giacobini-Zinner including this year's observations. Figure 1 showed that the ecliptic-plane component of the ΔV could be performed for about the same cost anywhere from February to July of 1985. We decided to perform this maneuver on March 1; it amounts to only 4 meters per second. The date of the out-of-plane component controls the size of the ecliptic component, but its range is only about 1 meter per second. The ΔV normal to the ecliptic will be applied on June 1, when it amounts to 33 meters per second. A small in-plane component can also be applied then, to correct any errors in the March 1 maneuver or updates to the comet's ephemeris.

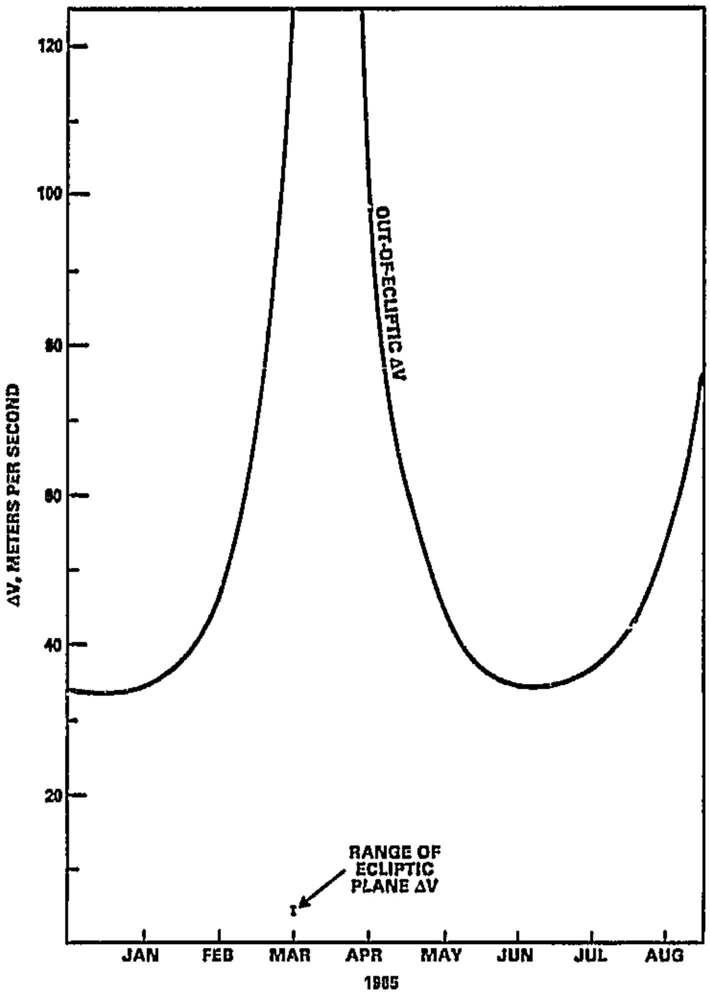

Fig. 2. ICE ΔV components to intercept Comet Giacobini-Zinner on 1985 September 11 at 11:00 G.M.T.

Targeting Strategy

ICE is currently targeted to fly through Comet Giacobini-Zinner's tail about 10,000 kilometers in the antisunward direction from the nucleus. The exact direction will be in the comet's orbital plane a few degrees from the antisun direction according to the best estimate for the aberration angle of the ion tail. We want ICE to pass close enough to the nucleus so that the spacecraft will pass nearly centrally through the tail in spite of possible ephemeris and aberration angle errors, yet far enough from the nucleus so that the tail's magnetic environment is well-organized and the potential hazard from dust particles is acceptable. The planned target distance will be selected from consideration of dust and ion-tail model studies currently in progress. We have several months to select the target position relative to the nucleus, since the ephemeris errors will likely be larger than the offset until a month or two before the encounter. We want ICE to survive at least through the closest approach to Giacobini-Zinner's nucleus, and hopefully the whole encounter. In 1985 October and 1986 March, ICE will be in upstream positions to monitor the Solar-wind input to Halley's Comet. It may be possible to use the Moon to capture ICE into Earth orbit for possible recovery in 2013.

OBSERVATIONAL COVERAGE OF COMET GIACOBINI-ZINNER FOR ICE

The astrometric needs of the ICE mission depend on the dates of planned comet targeting maneuvers. Before each maneuver, we need the best estimate of Comet Giacobini-Zinner's orbit. Hence, astrometric observations made a few weeks before a maneuver will be most helpful for updating the orbit in time for detailed maneuver planning. During the two to three weeks preceding the 1985 September 11th encounter, when Giacobini-Zinner will be near perihelion and most active, rapid turnaround of astrometric data will be important. The same mechanisms planned for quick reduction of observations of Halley's Comet can be used and tested for Comet Giacobini-Zinner.

Astrometric Accuracies

In order to have a high probability of crossing all significant parts of Giacobini-Zinner's ion tail, including the probable neutral sheet in the central plane, we hope to pass within ±500 km of the planned target. Figure 3 is an ecliptic-plane plot showing ICE's trajectory, as well as the orbits of Venus and Comets Giacobini-Zinner and Halley, relative to the Earth. At encounter, Giacobini-Zinner will be 0.47 astronomical units from the Earth, where 500 km subtends 1.5 arc seconds. The astrometric observations during the last few weeks before encounter should strive for this accuracy, which is only slightly worse than the accuracy of available AGK3 data along the comet's path. Perhaps more accurate AGK3R data could be used to reduce Lick Observatory plates to provide more accurate positions of the AGK3 stars along the path approaching the encounter. However, the comet will be active during this time, and its nucleus might not be definable to an accuracy better than that of the AGK3. Observations should be obtained during many nights of the last critical weeks in order to minimize the effects of errors in the constants of individual AGK3 plates. Astrometric observations obtained early in 1985 should be accurate to within ±2 arc seconds.

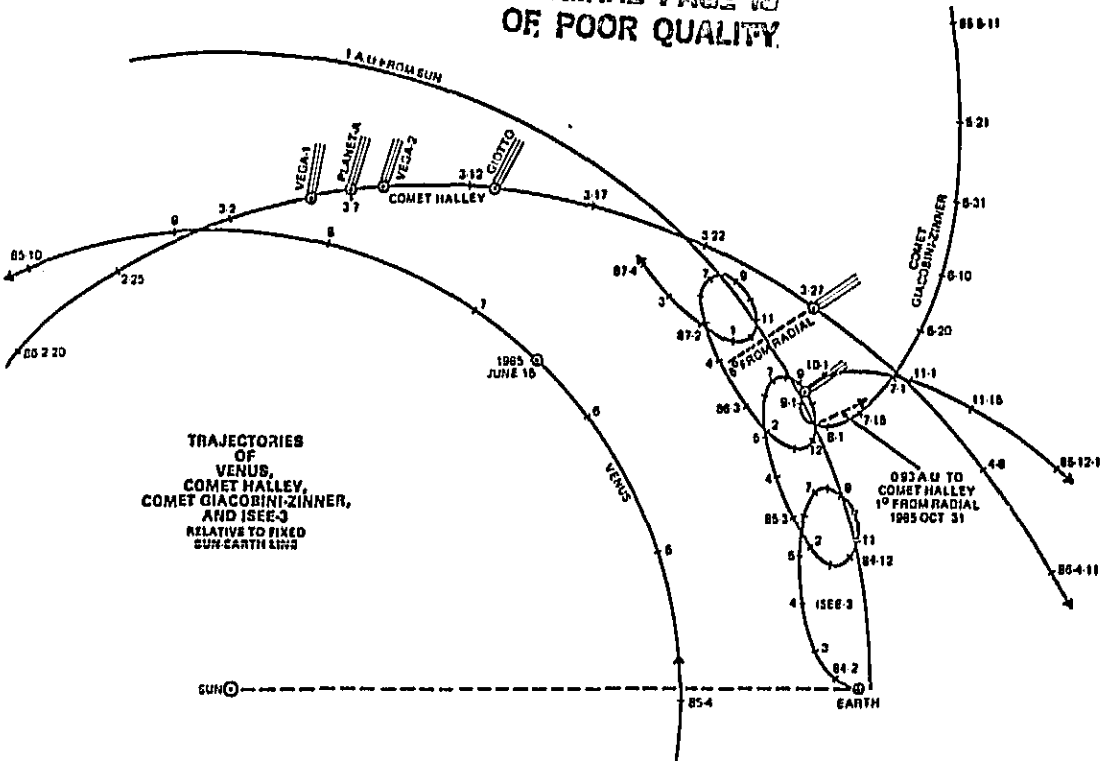

Fig. 3. Trajectories of ICE, Venus, and two comets relative to the Earth

Final Lunar Swingby Accuracies

We can use the close Lunar swingby of 1983 December 22 to estimate the accuracy of ICE's orbit determination relative to another celestial body. The times of Lunar occultation disappearance of the spacecraft observed at three tracking stations agreed to within 2 seconds of the predicted times. The spacecraft moved several kilometers in this time, but mostly along our line of sight; the angular error was less than 1". The distance of closest approach to the Moon, and the height above the Lunar orbital plane at the time, could be derived to less than 1-km accuracy using both pre- and post-swingby radio tracking data. The values for these parameters agreed within 2 km of the values predicted from pre-swingby tracking data alone. At the Moon's distance, 2 km subtend 1". Consequently, we believe that ICE's trajectory can be determined to within about 1" in the FK4 system from radio tracking data.

Conclusion

Astrometric observations obtained during 1985 January will be needed to update Comet Giacobini-Zinner's orbit for the ecliptic-plane maneuver on March 1. More observations in March and April will be valuable for the ecliptic-normal maneuver on June 1. Finally, intensive observations will be needed in late July through early September for precise targeting of the flyby on September 11. Observations early in this period will be important since the ΔV needed to correct a given error is inversely proporsional to the time remaining to encounter. The final targeting maneuvers during the last few weeks will depend on Jet Propulsion Laboratory's generation of updated comet ephemerides, which depend in turn on quickly-reported astrometric observations.

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REFERENCES

Djorgovski, S., Spinrad, H., Will, G., and Belton, M. J. S. 1984. Periodic comet Giacobini-Zinner (1984e). International Astronomical Union Circular 3937.

Farquhar, R. W. and Muhonen, D. P. 1979. The first libration-point satellite: Mission overview and flight history. Journal of Guidance and Control. 3:549.

Farquhar, R. W. and Dunham, D. W. 1981. A new trajectory concept for exploring the Earth's geomagnetic tail. Journal of Guidance and Control. 4:192.

Farquhar, R. W., Muhonen, D. P., and Church, L. 1984. Trajectories and orbital maneuvers for the ISEE-3 comet mission. American Institute of Aeronautics and Astrodynamics Paper 84-1976. (Seattle, Washington).

Marsden, B. M. 1982. Catalog of Comet Orbits (Cambridge, Massachusetts: Smithsonian Astrophysical Observatory), p. 62.

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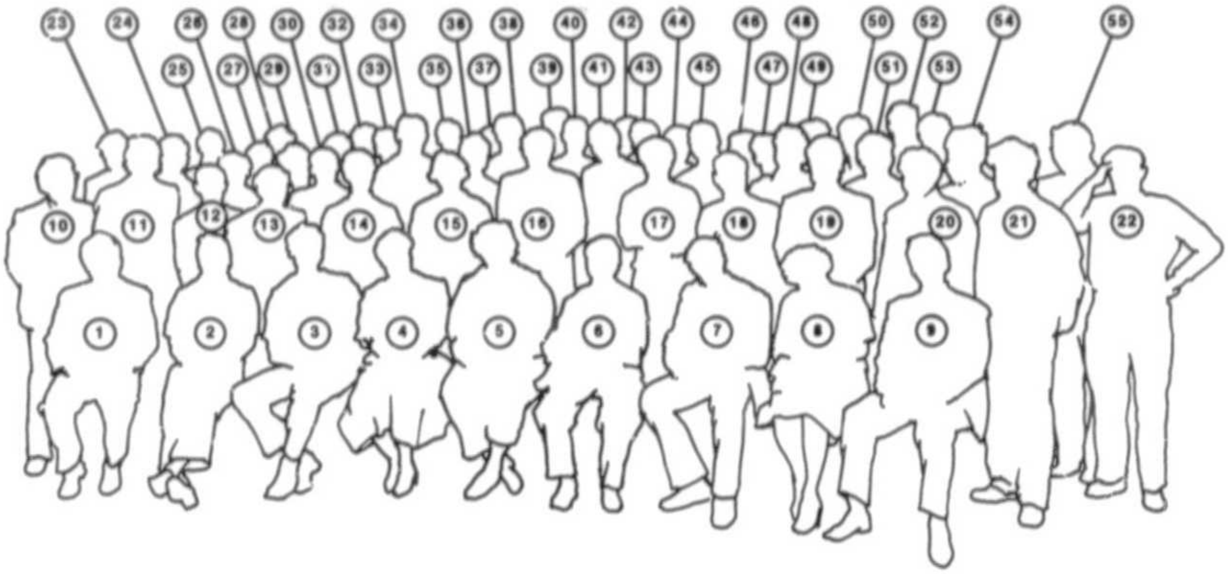

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