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TECHNIQUES FOR RULING IMPROVED LARGE DIFFRACTION GRATINGS

Massachusetts Institute of Technology
Spectroscopy Laboratory
with
National Aeronautics and Space Administration

MIT-DSR Project No. 76264

Project Director

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SUMMARY

The purpose of this project was to develop methods which would make possible the ruling of larger diffraction gratings, and gratings of higher quality, than were obtainable in 1966. This was to be done using extensions of techniques which we had developed during an eighteen year period, for controlling interferometrically the M. I. T. A ruling engine, applied to the 18 inch B engine, and to a proposed C engine of 24 inch capacity.

Although our primary object was to make contributions to the science and art of ruling diffraction gratings, progress could best be demonstrated by the production of actual master gratings which could be replicated and tested by use. Engine A had produced echelles and gratings up to 10 inches in ruled width, having excellent resolution and freedom from Rowland ghosts, but which showed stronger satellites and scattered light than was desirable.

Development of the B engine (1961 - 1970) resulted in the ruling of echelles of unparalleled size and quality. These were successfully ruled with spacings of 316, 79, and 31.6 grooves per mm, with blaze angles ranging as high as 79^{o}, and in sizes from 5" x 10" to 8" x 16". Replicas of these echelles are being widely distributed, and we have received enthusiastic report on their performance. Speed and resolution are unparalled; ghosts, satellites, and scattered light intensities are down by orders of magnitude. The B engine is now being set up in the Bausch and Lomb ruling laboratories for routine operation.

The fourth year of development of Engine C, of capacity 18" x 24", has now been completed. With it satisfactory gratings up to 12" x 15" have been ruled, and are in use in several observatories. As NASA support for our grating project comes to an end, we are engaged in improving the quality of the C engine rulings at higher angles than 25^{o}, with the hope of being able to rule 16" x 24" master echelles, capable of use at angles up to 65^{o}, within the next 18 months.

Problems of stability control and diamond wear increase very rapidly with grating size and that of the ruling engine, but we are now able to rule grooves of excellent section and uniformity up to 16 inches long, at rates up to 12 strokes per minute.

Present limitations of the engine, which are now gradually being reduced, are:

1. Occasional variations in groove spacing of up to one-half fringe, occurring over periods of five to twenty hours, which are believed to

originate in instability of the fused silica straightedge used for lateral control of the diamond.

2. Residual thermal currents of low amplitude in the large mass of the engine.

3. Wear of the ruling diamond in ruling more than 100,000 linear feet of groove, causing a variation in blaze angle across the face of the grating.

4. The natural increase in probability of an electronic or mechanical breakdown during the longer periods of time required for ruling a large grating with high groove density. A 12" grating requiring 135,000 feet of grooves has been attempted six times, with a different cause for non-success each time. However, such breakdowns occur with less frequency as we improve the engine and gain experience with it.

The groove spacing problem is being attacked by installation of a larger and more rigid fused silica straightedge of 23" length, which we expect to receive within the next few weeks, and which the engine is now being modified to accept.

The improvements in grating size and quality resulting from this project are believed to arise from:

1. A philosophy of bringing mechanical excellence only to a level readily reached, with necessary further correction being carried out by optical and electronic means.

2. Interferometric servo-control of the translation of the blank carriage, and elimination of its yaw.

3. The type of interferometric control used, which involves moving the blank continuously rather than intermittently, thus reducing errors arising from elastic and frictional variation.

4. The special type of diamond carriage we designed for engine A, in which the diamond is guided by a fused silica straightedge, thus facilitating the ruling of long, straight grooves.

5. Continuous or frequent monitoring of all moving parts of the engine, recording to 0.001°C the temperatures of its critical parts, and introducing careful corrections for atmospheric pressure variations.

The C engine, whose progress has been followed in a series of eleven semi-annual reports to NASA, will be fully described in the literature as soon as its development has been completed. References are given herein to descriptions of the A and B engines.

In addition to its support from NASA, for which we are extremely grateful, the M.I.T. grating-ruling program has received and continues to receive, support from the Air Force Cambridge Research Laboratories, and from the National Science Foundation.

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DETAILED REPORT

During the years 1948-1961 the M. I. T. grating-ruling program was concerned with the development of the first engine to be controlled through servo-mechanisms by means of light waves. This, the A engine, of 10 inch width ruling capacity, was constructed of parts obtained from the University of Chicago from an old ruling engine of Michelson and Gale. When assembled, its errors of positioning were found to have been increased by warpage and wear to some 600 times those tolerable for grating ruling. Ways were developed of removing these errors by interferometric control so that by 1955, gratings and echelles up to 10 inches in ruled width had been produced which were superior in resolving power, freedom from Rowland ghosts, and low intensity of satellites, to gratings previously available, and these could be blazed and used effectively at higher angles than were previously useful. Replicas of these gratings are in wide use still, but suffer somewhat from undesirable amounts of scattered light. (Ref. 1- 15)

Having demonstrated with the A engine the capabilities of interferometric control, and hoping to be able to fill the need for still larger gratings and gratings which could be used at higher angles, with weaker false light, we decided in 1961 to attempt conversion of an industrial measuring machine into a ruling engine by applying interferometric control. A No. 3 Universal Measuring Machine was obtained from the Moore Special Tool Co. of Bridgeport, Conn., with several minor mechanical modifications, and we provided this with interferometric controls over blank translation and yaw. The development of this engine, and its ultimate success in ruling outstanding gratings and echelles up to 8" x 16" in ruled area, at blaze angles between 63^{O} and 79^{O}, with groove spacings between 10 and 100 red fringes, has been described in NASA, NSF, and AFCRL reports and in the literature (Refs. 17-18).

The ultimate success of the B engine took place between 1966 and 1970 and involved use of laser monochromatic light (6328 A) instead of that from a mercury isotope lamp (5461 A), which made possible controlled translation over distances greater than 10 inches. Other progress involved improved understanding of frictional, elastic, lubrication, interferometric, servo-mechanism, temperature control, and atmospheric pressure corrections, but our basic method of interferometric control was not altered, despite experimentation with other possible methods. The experience with the A and B engines was invaluable in designing the C engine, whose construction began early in 1966. The B engine has now been transferred to Bausch and Lomb, who have furnished numerous replicas from the masters ruled on our program, and have been most helpful in providing diamond tools and coated blanks.

The C engine consists of a Moore No. 4 Universal Measuring Machine, with 24" x 36" capacity, to which interferometric controls were applied. The Z ways were removed, a yaw table was added, the end thrust bearings were changed from ball-bearings to graphitar, and a monorail and diamond carriage of the design we had used previously were constructed. "Porches" were added at both ends of the machine to hold control and test lasers.

The altered mechanical engine was delivered to our laboratories at the end of 1966, and was mounted on an 11-ton anti-vibration mount with Barry air controls. It was provided with a long monorail and straightedge to give a stroke of the diamond carriage up to 18", and a yaw correction table capable of holding a blank up to 18" x 27" x 5" in size. It was then fitted with optical, electronic, and servo controls which were able to keep the blank carriage moving in a line deviating from straightness by no more than 1 part in 10^7, or about 1/50 second of arc. The engine is shown in Fig. 1.

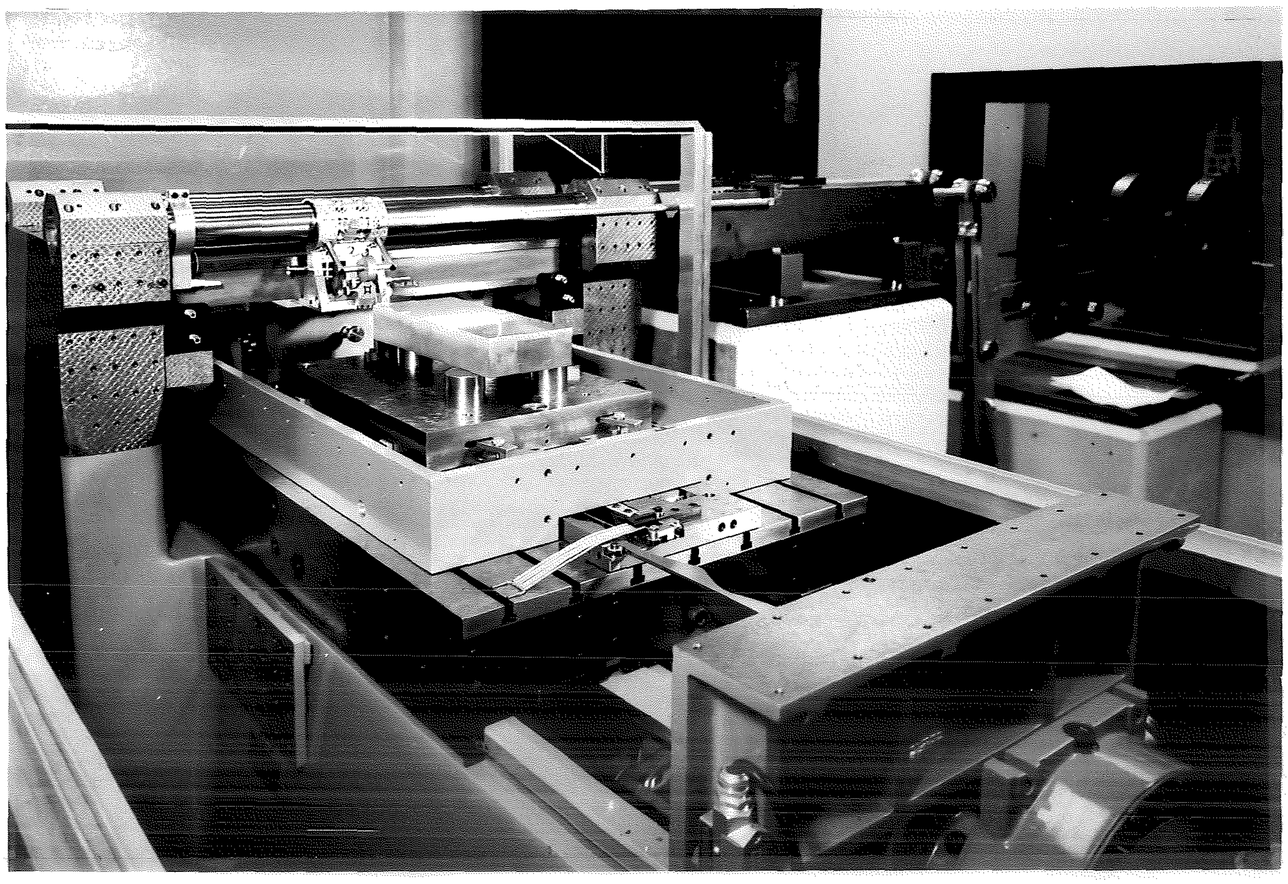

Fig. 1 - The C Ruling Engine

The periodic error of the screw, about 5 fringes in amplitude, was reduced to less than one fringe by installation of the new bearings. Construction of a drive mechanism, shown in Fig. 2, was carried out by the M. I. T. shops.

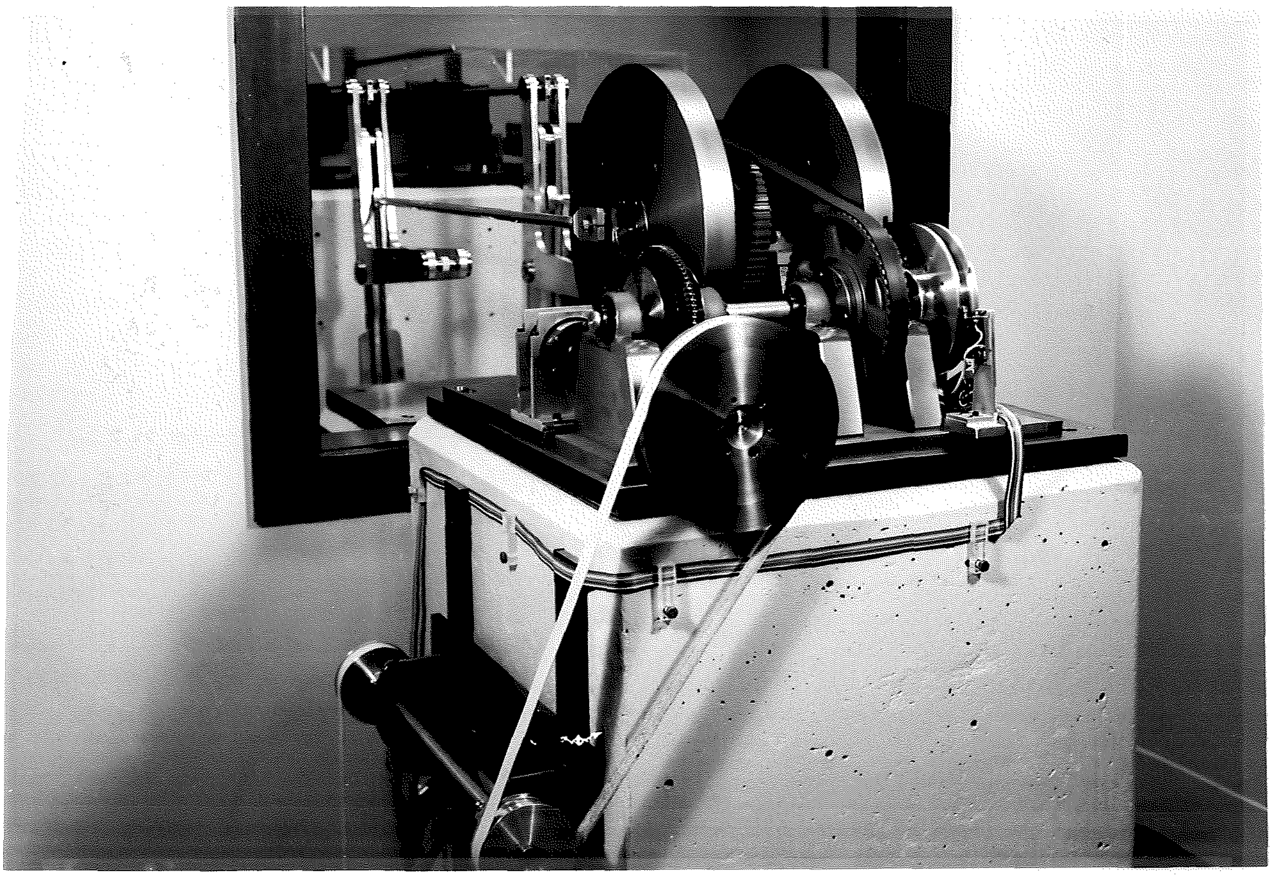

Fig. 2 - The motor drive for the C engine, with heavy flywheels for reducing "belt ghosts".

The original nitralloy straightedge obtained from Moore was found to produce undue diamond button wear, and a spare fused silica bar designed for the B engine was substituted. This was found satisfactory as to wear, but bent too much for use with groove lengths greater than 12 inches. A new straightedge 23" x 4" x 3 3/4" is now being fabricated, and new end mountings are being installed to hold it adjustably but rigidly in the engine.

During the test period facilities were installed to permit chart recording of blank motion, translation correction, yaw control compensation for non-linearity of ways, laser stabilization, engine temperature in several locations, engine room, anteroom, and laboratory temperatures as controlled by air conditioning and modulated electric heat, atmospheric pressure variations, and pressure correction applied. Several small test interferometers were mounted to detect straightedge motion, diamond carriage button wear, straightedge bending, and engine and floor vibration.

Various types of diamond lifter were constructed and tested for use with very long ruling strokes. Electrical, hydraulic, pneumatic, vacuum, and mechanical lifters and their combinations were tried. A purely mechanical lifter was found satisfactory for speed, uniformity, and reliability of response. A correction mechanism to compensate for variations in control wavelength with atmospheric pressure was installed, using an electrical analogue computer in place of the mechanical computer used in Engine A. By the end of 1967 the C engine was in test operation ruling gratings.

Fig. 3 shows the control panel mounted in the engine anteroom, in which are housed the electronic and servo-controls, and the chart recorders which monitor the engine's condition and performance.

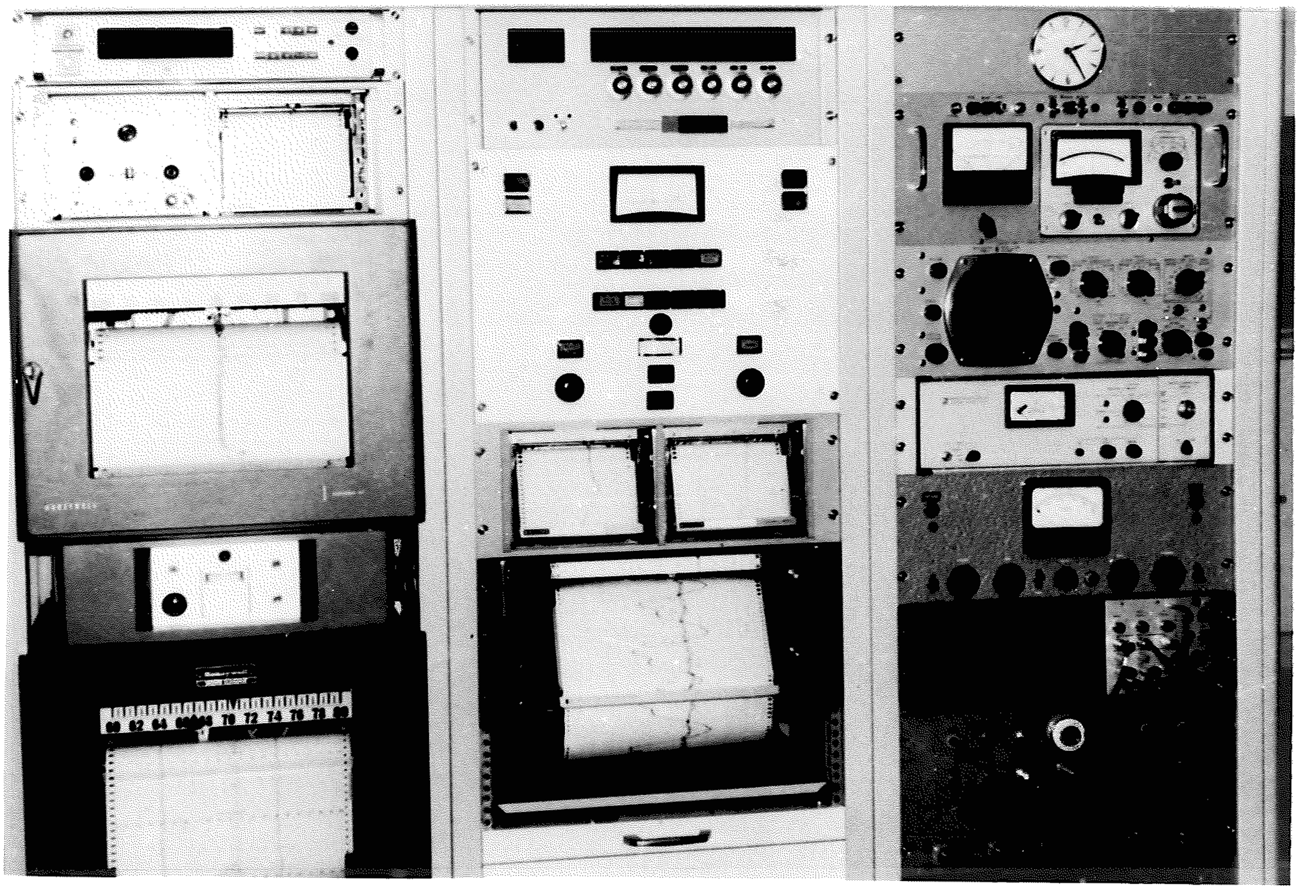

Fig. 3- Control panel of the C Ruling Engine

Fig. 4 shows the type of correction curve plotted by the correction computer as it compensates for screw, gear, and bearing translation errors, and moves the blank being ruled ahead uniformly at about one foot per week. The curve marked "rotation" is the yaw control plot, which shows deviations from linearity of motion which were compensated for by rotation of the blank.

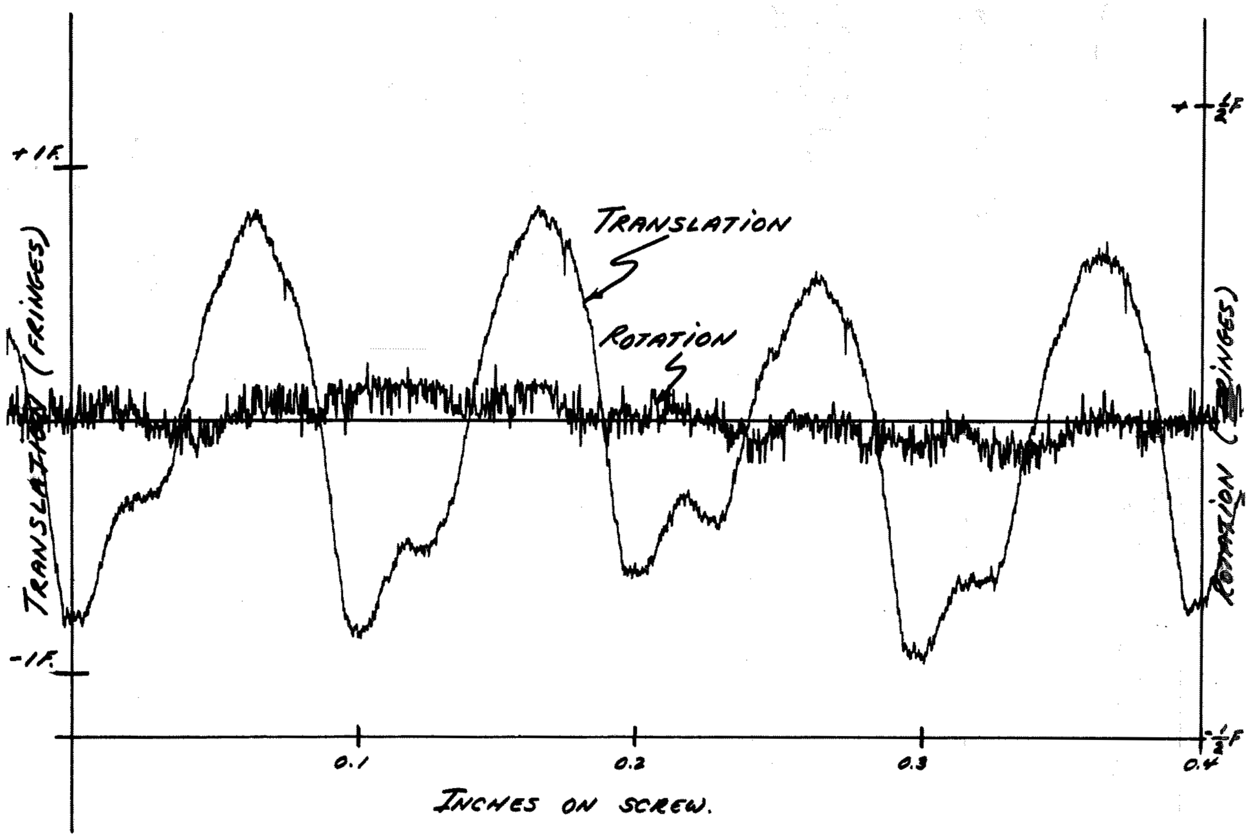

Fig. 4 - Translation and yaw correction curves for several turns of the blank carriage driving screw.

Because of its much larger size and longer stroke than previous ruling engines, the elimination of errors arising from thermal and elastic effects in the C engine is much more difficult than with smaller engines. By the middle of 1969 it was ruling very satisfactory gratings in sizes up to 12" x 15", of which two were delivered to the Jet Propulsion Laboratory in Pasadena and one to Kitt Peak Observatory. All gratings were tested before delivery on our 6" Twyman-Green interferometer for linearity of wavefront, and on our 40 ft. 17" aperture test spectrograph for blaze angle, efficiency, resolution, ghost and satellite intensities, and amount of scattered light. The engine is now at about the stage of ruling excellence and reliability at which the B engine was two years before completion.

After attempting six times the ruling of a 12" x11.5" master grating with 452 grooves per mm for the Mt. Wilson Observatory, we decided in mid-1970 to reconstruct the superstructure of the C engine. Although the gratings ruled by it had been larger than those previously obtainable, they were designed for use at lower angles than 25°, and showed occasional errors in groove placement some five times as large as those occurring in most B engine gratings. Since our ultimate aim (which we hope to achieve by June 30, 1972) is to rule 16" x 24" echelles blazed at 63°, we decided to concentrate on finding the source of these variations.

One source proved to be minute thermal currents originating from the control laser. This was then air-cooled separately from the engine case, and its temperature can now be brought to within less than 0.010°C. from that of the main body of the engine. At the same time the sensitivity of the engine to temperature changes was lowered by diminishing the distance between the ruling plane and the fixed mirror control plane, and by mounting the moving interferometer mirror directly on the end of each fused silica or Cer-Vit blank being ruled.

Another source of difficulty was found to be instability of the diamond straightedge, whose 1 1/4" x 2 1/2" section proved too slender for the long grooves desired. It is now being replaced with a member which is 3 3/4" x 4" in section.

An inherent difficulty in the ruling of large gratings is diamond wear, which involves a change in the angles of the sides of the grooves across the face of the grating, and hence diminished blaze efficiency; when chipping of the diamond occurs, line satellites may be introduced. Diamonds are found to vary greatly in hardness and wear resistance, and the best results are obtained by re-sharpening a diamond tool with a good history of standing up while ruling 135, 000 feet of grooves.

We are now testing the relative influence of gold and aluminum coatings on diamond wear, and new rulings are being carried out on gold-coated surfaces, which can be coated with aluminum after ruling. Use of wide groove spacings is most effective in reducing diamond wear; although deeper and wider grooves are then needed, fewer are required, and the diamond rides on a larger area of its surface. It must be borne in mind that the groove spacing chosen has no influence on resolving power and dispersion, so long as the angles of illumination and diffraction remain constant. It affects only the free spectral range, which controls overlapping of orders.

A further improvement of the C engine which we hope to inroduce as time permits involves replacement of the gears and toothed belts which turn the flywheel shaft of the diamond drive. New gears have been cut with errors in tooth placement and shape approximately one-tenth as great as those in the commercial gears now being used. Although "belt ghosts" have been reduced to acceptable values, this change should bring them safely within the 10^{-5} intensity range relative to each master line.

It will be necessary to conclude the M. I. T. grating ruling project by June 30, 1972, and we are giving thought to the future of the C engine, which should be in good operation by that time. It should perhaps be transferred to an astronomical observatory for operation, since much of the demand for gratings larger than 16" in ruled width can be expected to come from astronomers. In the meantime, support to the concluding date for the project from M. I. T., Bausch and Lomb, the Air Force Cambridge Research Laboratory, and National Science Foundation appears assured, and every effort will be made to complete the C engine by then.

This project would have been impossible without the support furnished by NASA and the other agencies cited, as well as that from Bausch and Lomb, whose cooperation over some 24 years, especially in regard to such expensive ancillary activities as provision of grating blanks, coatings, diamond ruling tools, replication, and testing of rulings, has made it possible for us to concentrate on problems of engine development.

The understanding cooperation of M. I. T. authorities in permitting the continuation of the project under the direction of the Principal Investi-

gator for several years after his retirement, is much appreciated.

The following list of personnel covers only the years of NASA support of the project, but includes all who participated at M. I. T. whether supported by NASA or other funds.

Dr. George R. Harrison, Principal Investigator.

Stephen W. Thompson, Engineering Assistant.

Harry Kazukonis, Electronics Technician, later Engineering Assistant.

Joseph R. Connell, Electronics and Optical Technician.

Joseph Yena, Shop Foreman

William Davis, Instrument Maker

William Pendleton, Instrument Maker

Wallace Welch, Instrument Maker

Emmanuel Machi, Instrument Maker

Axel V. Erikson, Machinist

George W. Whitney, Machinist

John W. Glendening, Part-time Student Assistant

William Bloomquist, Student Assistant

Ellen C. Gavin, Secretary

Andrea B. Goodzeit, Secretary

George R. Harrison

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