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Present status of research on space optical remote sensors at CIOMP

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Abstract: This paper is to review our space optical remote sensor(SORS) technologies including optical materials, optics fabrication and coating, optical testing, system assembly and final testing, and space environment simulation experiment conducted in our institute. The primary parts of the fabrication and testing facilities and results are described in detail.

Key words: space optics; optical remote sensing; optical material; optical fabrication and inspection; optical system assembly and testing
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1　Introduction

With the rapid technology development, space optical remote sensor (SORS) appears to be playing more and more important role in earth environment protection, national economic development and defense. Basically, it is a multidisciplinary high-tech product integrating with optics, mechanics, electronics, material technology, and computer technology. As the cradle of optics research in China, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese academy of sciences (CIOMP) has been doing research and development in all those fields for decades. Strongly government funded national aerospace engineering projects have been carried out in recent years. 10 years of efforts have made our institute the state of the art SORS research center in China.

2　Optical material

The SORS requires large size and high quality optical glass, which typically has clear ape- rture of 500~ 700 mm in diameter with nearly ideal optical uniformity and residual strain. To meet the requirement, ultra-precision annealing furnaces with extreme stability, temperature control accuracy and long annealing cycle, and corresponding testing equipment have to be used. Therefore, we modified the old furnace system and setup in the testing lab.

For the furnace system, a buffered isolation layer has been added to avoid ambient thermal shock, a new type of heat insulation material has been used, and more monitor points have been added to improve the temperature stability. The upgraded furnace system has a chamber with size of Φ1300 mm × 360 mm. The chamber can be heated up to 700 ℃ with less than 0.2 ℃ radial temperature gradient. The heating up and cooling down rate are less than 30 ℃/h and 0.02~ 5 ℃/h, respectively. Fig. 1 shows the schematic diagram of the precision annealing furnace system and the control equipment. Using this modified system, we have been able to make superior grade optical glass, which has refractive index uniformity of 1.5×10^{-6} over size of 700 mm in diameter.

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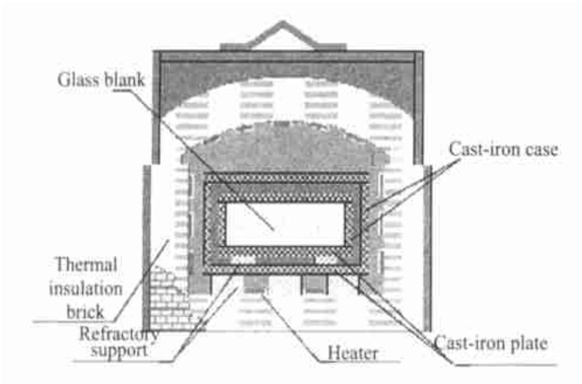


(a) The furnace schematic diagram

(b) The control equipment

Fig. 1　The precision glass-annealing furnace for large size and high quality optical glass

The large size optical glass-testing lab shown in Fig. 2 covers 103 m^2 area. Half of the area is dedicated to the temperature-stabilizing room with a variation of less than ±0.5 ℃. It is constantly ventilated to keep the air purified, to maintain constant temperature and humidity, and to exhaust toxic gases. There is a large air-bearing vibration isolating table with a dimension of 5 m × 1 m × 1.2 m. On the table there is an optical testing setup, which contains the sample testing work bench with working distance of 600 mm, knife-edge interferometer and image processing system with measurement accuracy of better than λ/10 P-V, a pair of contact glass plates used for uniformity testing with effective size of 300 mm in diameter and surface accuracy of better than λ/10P-V, and standard spherical reflectance mirror with size of 400 mm in diameter, curvature radius of 4 m, and surface accuracy of better than λ/10 P-V.

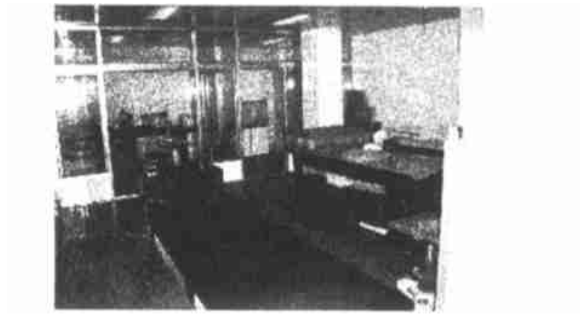


Fig. 2　The optical glass specification testing lab

Currently this lab can be used to test the optical glass uniformity over an area of up to 800mm in diameter. Up to date, precision annealing and uniformity testing have been done for more than 40 pieces of large optical glass which are in various sizes of Φ720×130 mm, Φ800×140 mm, and Φ590×60 mm, etc. Furthermore, to verify the consistency, over 20 pieces of high strength and radiant resistant window glass with a size of Φ565×70 mm bought from Russia have also been tested. The results coincide with those from Russia. It needs to be mentioned is that the refractive index uniformity of all glass fabricated here can reach to 1.5×10^{-6}.

3　Optical fabrication and coating

The SORS requires the optical reflectance mirror to be lightweight. In the early stage, we modified the numerically controlled drill machine and set up the machinery center. Finally we developed a universal optical mill, which can process quartz glass, crystallite glass and optical glass up to 600 mm in diameter. The blind aperture can be in circular, rectangular, trapezoid, hexagonal, or other irregular shapes. The inner circle diameter ranges from 12 mm to 60 mm. Both the aperture size and position accuracies reach to ±0.02 mm. The thickness between adjacent apertures can be as small as only about 3 mm, so that the weight can be greatly reduced by over 50% without sacrificing the surface accuracy. The measured accuracy is better than λ/10 P-V.

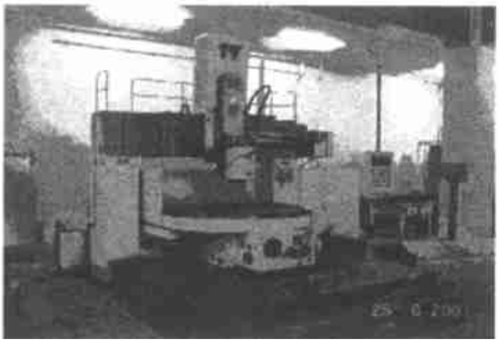


Fig. 3　Φ2 m universal optical mill for grinding

For the process of coarse grinding, finish grinding and polishing, Φ800 mm vertical universal optical mill shown in Fig. 3, Φ800 mm single axial precision polishing machine and corresponding spherical concentricity checking equipment have been used. They are able to shape, polish the planar and spherical optics of 800 mm in diameter with concentricity checking accuracy of 2". The surface accuracy for spherical optics of 700 mm in diameter achieved λ/10 P-V. The fabrication process for large size and high precision planar optics is handled by 1.5 m and 3 m planar circular polishing machines. The maximum size can be 1.5 m in diameter. The surface accuracy can reach and close to λ/10 P-V for Φ560 mm and Φ790 mm, respectively.

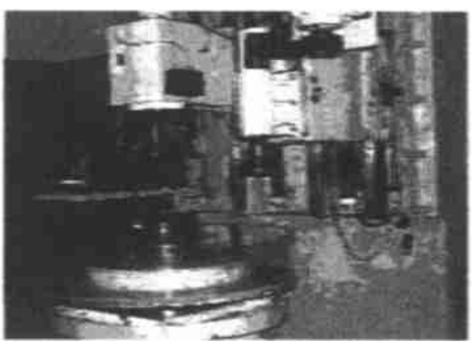


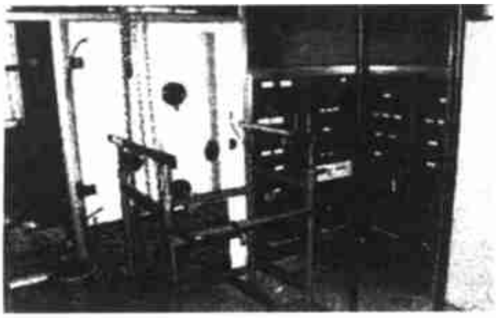
Fig.4　FSGJ-1 Φ800 mm aspheric numerically controlled machine

Aspheric optics are very important in SORS, which can simplify and minimize the optical system, reduce the weight and improve the image quality. Particularly the off-axis aspheric optics has the advantage of realizing large field of view without center obscuration. Therefore, we developed FSGJ-1 Φ800 mm aspheric numerically controlled machine shown in Fig. 4 and CNC Φ2 m numerically controlled machine shown in Fig. 5. The first one can process both co-axis and off-axis mirrors in a maximum size of Φ800 mm with λ/40 RMS surface accuracy and 3 nm RMS surface roughness.

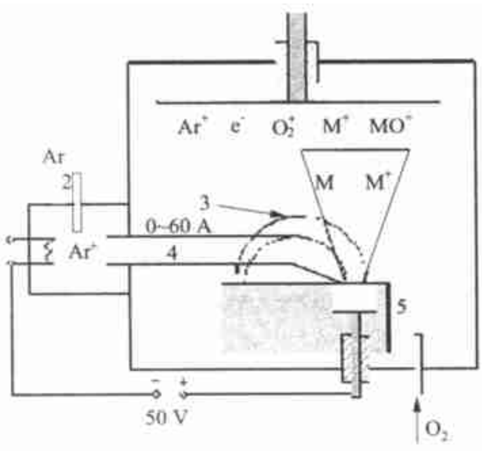
Fig. 5　Φ2 m CNC numerically controlled optical fabrication center

Optical coating is also an important technique in SORS. For high reflectance and anti-reflection coatings, the reflectance should be above 97% and below 0.4% in the 0.5~ 0.9 μm wavelength region, respectively. For transparent and electric conducting coating, visible light and infrared reflectance should be less than 10% and above 90%, respectively, and meanwhile electrically conducting. For infrared cut-off coating, visible light transmittance has to be close to 100%, while for beam splitter coating, transmittance and reflectance need to be nearly equal without polarization effect.

Apart from the above requirements, the coating layer has to be very stable to withstand the space environment. We modified the e beam evaporator to become an ion-assisted one shown in Fig. 6, which greatly improved the layer density and stickness. The vacuum chamber size is Φ 1100 × 1250 mm. The base pressure and e-beam gun working pressure are less than 4×10^{-4} Pa and 1×10^{-4} Pa, respectively. It takes about 25 minutes to pump down the chamber. The substrate holder can support sample size of Φ800 mm and weight of 150 kg. During evaporation, the substrate temperature is only tens of centigrade, which has little effect on the surface profile. Fig. 6(b) shows the working principle for the ion-assisted e-beam evaporator. To further improve the layer quality and performance, a vacuum-annealing furnace has been added. This furnace has effective working space of Φ 1300 mm × 900 mm; the maximum temperature is 900 ℃. The ultimate vacuum pressure is 3×10^{-4} Pa. Heating up rate is 0.5~ 10 ℃/min.



(a) The evaporator



(b) The working principle

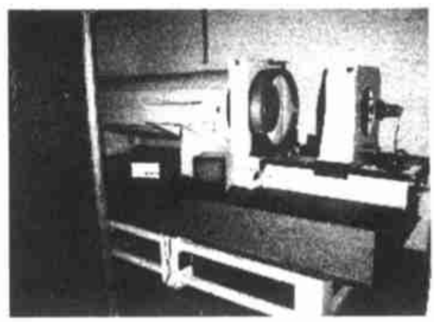
Fig.6 Φ100 mm optical ion-assisted e-beam evaporator

4 Optical testing

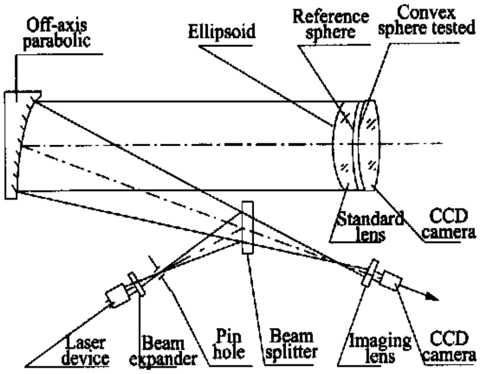
The optical elements for the space optical system have large size and various surface profiles. The fabrication needs extremely high accuracy. The testing cannot be done by regular method. Therefore, we developed a series of testing equipment.

The knife-edge interferometer is used to measure the profile of the large curvature concave spherical surface. Small part of the surface is chosen as a reference to test the whole surface. As the reference and test light share the same optical path, it is insensitive to the vibration and air turbulence. This is particularly good for the surface measurement of large curvature and large size spherical mirrors. For instance, for the concave spherical mirror of 700 mm in diameter and 26 m in curvature radius, the surface profile accuracy can reach to λ/10 P-V. This interferometer also has image processing functionality to process the interferogram It can quantitatively give the P-V, RMS value, surface contour map and 3-D graph.

The plane and convex spherical surface laser interferometers are used to characterize the profile of the large size plane and convex spherical surfaces. The size can be as large as 500 mm in diameter. Curvature radius can be 6 m. Measurement accuracy is λ/10 P-V. Fig.7 shows the optical system diagram and its photo for the interferometer.



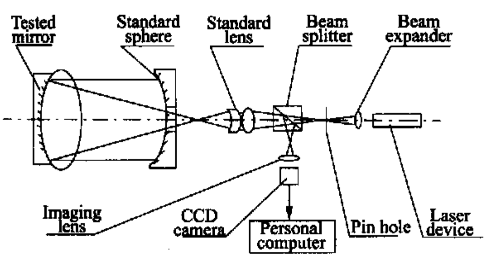
(a) The Φ500 mm interferometer



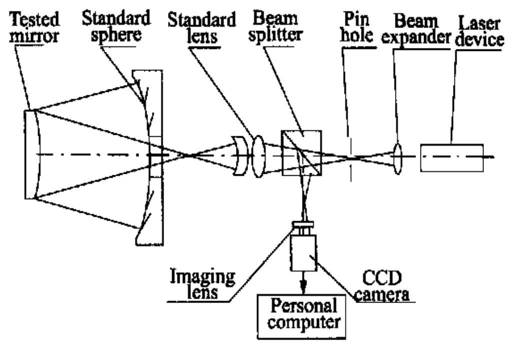
(b) The optical system diagram

Fig. 7　Φ500 mm plane and convex spherical surface laser interferometer

The aspheric interferometer is used to test both primary and secondary mirrors of the aspheric optical system. As both mirrors are hyperboloid, aberration-free point auto-collimating interference optical path is chosen. Fig. 8 shows the basic working principle and its photo of the interferometer. Need to be mentioned is that the accuracy is improved to $\lambda/10$ P-V because the light will be reflected twice on the testing surface while only once on the reference surface. While this is for the final testing, Offner compensator and Zygo interferometer are used for in-situ accuracy measurement during the fabrication of aspheric optics. The result is consistent in comparison with the previous one. To make further verification, we measured the aspheric mirror bought from Russia, which was originally measured with zone plate compensator. The result is also compromise with ours. Therefore we believe the aspheric mirror achieved $\lambda/40$ RMS accuracy.



(a) Interferometer principle for aspheric primary mirror

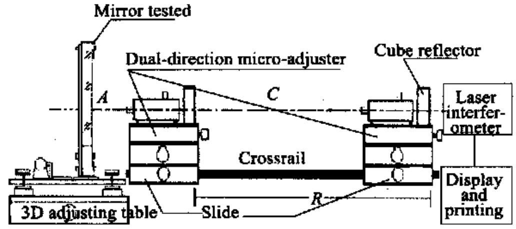


(b) Interferometer principle for aspheric secondary mirror

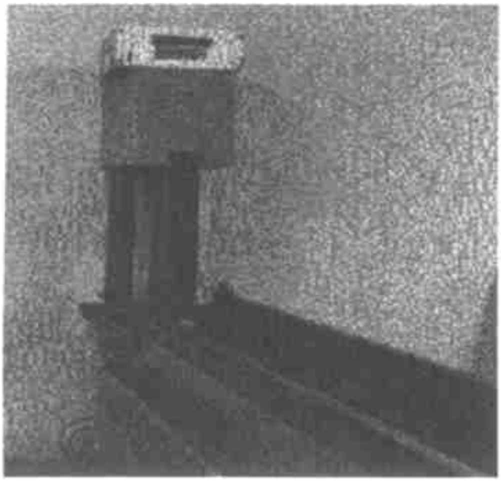
(c) The interferometer

Fig. 8　The aspheric interferometer

The long curvature radius measurement apparatus is used for large size optics. It consists of 6.5 m-long precision rail, vibration isolation table, and double frequency laser interferometer. It is capable of measuring mirrors having size of 200~600 mm in diameter and curvature radius of 500~6500 mm with 0.01% relative accuracy. Fig. 9 shows the measuring equipment.



(a) The schematic diagram of the measurement apparatus



(b) The double frequency laser interferometer

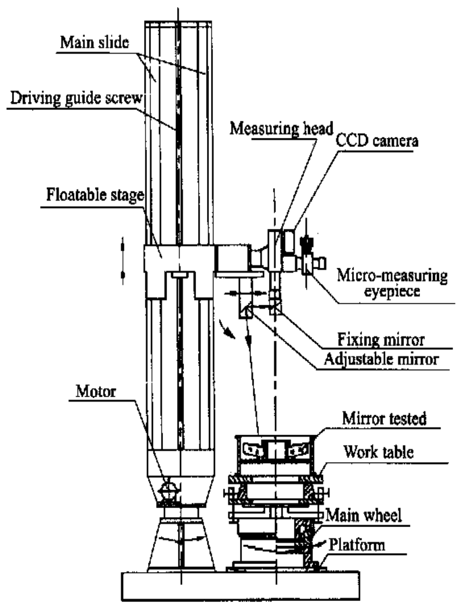
(c) The aiming apparatus for measuement

Fig. 9 The long curvature radius measuring equipment

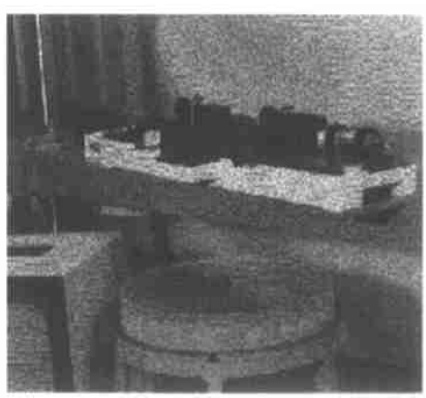
5 Optical system assembly and testing

The final system assembly for the SORS requires tight centricity of all the elements. Therefore, we developed a large size optical system-centering instrument shown in Fig. 10. The stage is 900 mm in diameter. The traveling distance for the vertical rail is 1. 8 m. The centricity can be measured by naked eye, CCD TV and laser interferometer with less than 1” accuracy. The major axial jitter is less than 0. 5” and radial swing is less than 0. 5 μm. The targeting accuracy can achieve 0. 15” in the centricity interference measurement.

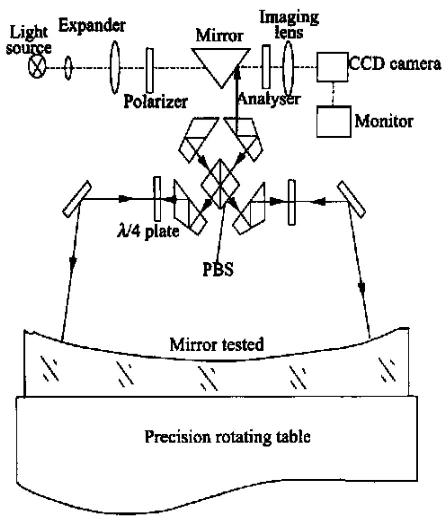
(a) The photo of the centering instrument



(b) The centering instrument schematic diagram



(c) The centering interferometer

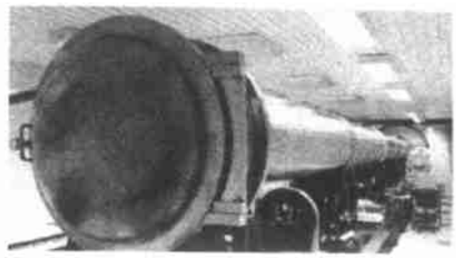


(d) The centering interferometer working principle

Fig. 10 The centering instrument for final system assembly

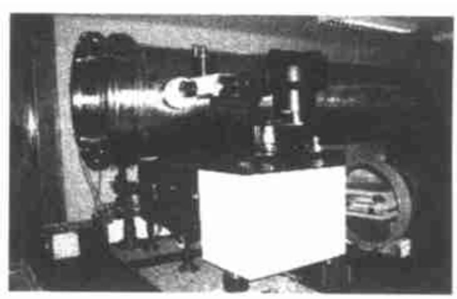
The general performance testing of the whole system is conducted in the testing lab, which is clean, and temperature constant over area of 100 m^2. There is a 15.5 m long air-bearing isolation table, on which a Newtonian collimator and a moving subject simulator are supported. The collimator has a focal length of 13 m and diameter of 650 mm. The wave front difference is less than λ/5 P-V. Fig. 11 is the general performance-testing lab.

The collimator can be used for star-point test, visual resolution test, static and dynamic photographic resolution test of camera, and the camera modulation transfer function (MTF) measurement. To measure the dynamic photographic resolution, the moving subject simulator has been developed. Fig. 11(c) shows its schematic diagram. The moving subject has a space frequency of 3.65 ~ 50 lp/mm, spectral range of 500 ~ 900nm and contrast of 100 to 1. The speed-height ratio (V/H) can be adjusted in the range of 0.01 ~ 0.08rad/s with relative error of less than 0.1% measured at V/H of 0.026rad/s. The focus can be adjusted in the range of ±80mm with 0.01mm accuracy. Yaw range and positioning accuracy are ±30° and ±5′, respectively.



(a) 13 m collimator

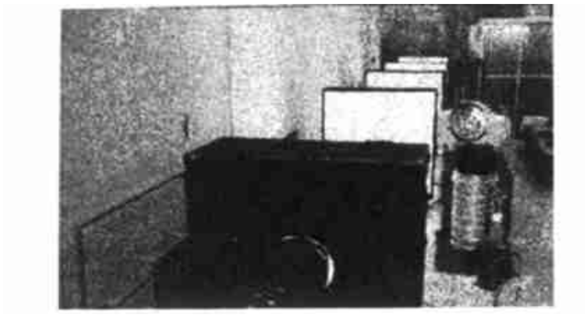
(b) 15.5 m air-bearing vibration isolated table



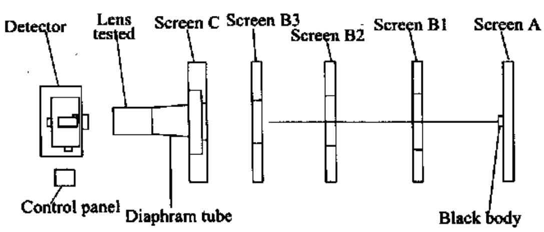
(c) The moving subject simulator

Fig. 11 The general performance testing lab

MTF is an extremely sensitive measure of image quality. The MTF measurement system for long focal length optical system has been developed. This system is capable of testing lens having maximum focal length of 4 m and maximum size of 650 mm in diameter, in the space frequency range of 0 ~ 200 lp/mm, spectral range of 400 ~ 900nm with 5% accuracy. It can also measure the MTF of the sensor which include both of camera lens and CCD.



(a) The device



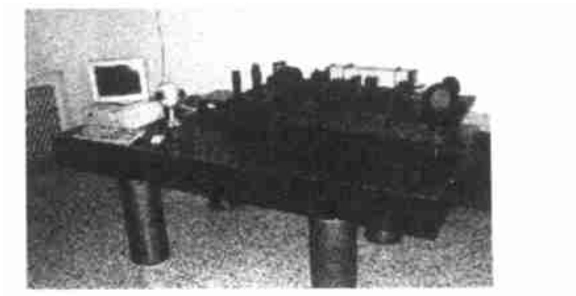
(b) The schematic diagram

Fig. 12 The stray light coefficient-measuring device

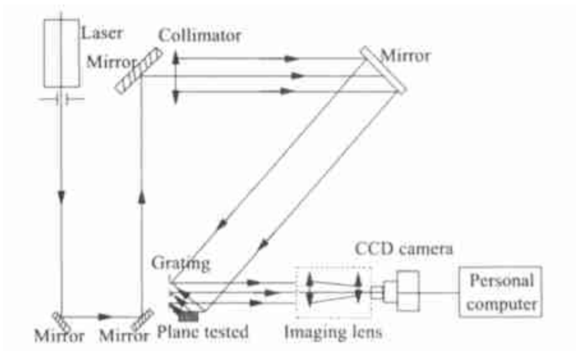
A stray light coefficient measuring device for the SORS shown in Fig. 12 is capable of measuring lenses with maximum size of 500 mm in diameter and maximum focal length of 2.7 m in the spectral range of 0.5~ 0.8 μm. The measurement repetition accuracy can reach 0.005.

Apart from those above mentioned, corresponding equipment has been developed for long-focus large-size lens transmission measurement, distortion measurement, precision focal point testing, shutter speed and image exposure measurement, and auto-collimation interference wave front difference measurement, etc.

Dynamic interferometer was developed to control the quality of the camera assembling; it can measure the film unevenness dynamically, while the film is attracted by vacuum on the film stage. The film area is 127 mm × 127 mm, film unevenness measuring accuracy is 1 μm, and shutter speed is 1/60~ 1/1000 s. The sampling rate is 20 fps.



(a) The interferometer configuration



(b) The working principle

Fig. 13 The film unevenness dynamic measuring interferometer

CCD jointing machine shown in Fig. 14 is used to assemble CCD elements. The stage has traveling distance of 200 mm and 100 mm along X and Y direction with less than 2" accuracy. The microscope objective has magnification of 20 ×, focal length of 36.055 mm, numerical aperture of 0.35, and object working distance of 43.17 mm. The object and image plane are 0.3 mm and 6 mm in diameter, respectively. The total magnification can reach 1000 × when received by TV camera and monitored on screen. The jointing accuracy of the linear array CCDs is better than 0.002 mm along the CCD array direction and its width direction, and the jointing unevenness is better than 0.004 mm by using this CCD jointing machine.

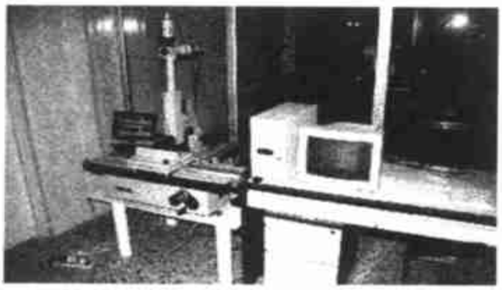


Fig. 14　The CCD jointing machine

Fig. 15　The CCD performance measuring instrument

Fig. 15 shows the configuration of the CCD performance-measuring instrument developed in our institute. The CCD performance includes the geometrical, optoelectronic parameters and MTF. The geometrical parameter includes CCD pixel size, distance between pixels and flatness. Geometrical measurement range is 200 mm with 1.5 μm accuracy in lengthwise and 1mm with 1.5 μm accuracy in widthwise. Flatness measurement range is 1 mm with 2 μm accuracy. CCD MTF measurement accuracy is 5%. CCD opto-electronic parameter measurement includes spectral response, dynamic range, linearity, saturation exposure, equivalent noise, and response uniformity among the pixels.

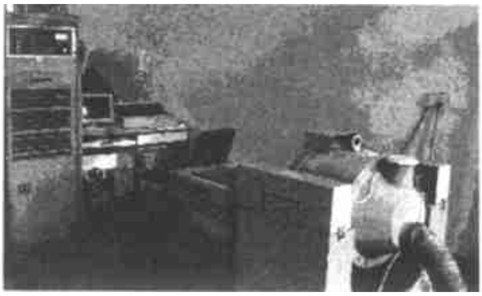
We also bought a Kodak film developing equipment for developing the film and finery testing SORS photographic resolution.

Currently we are fully capable of fulfilling the final assembly and testing using the equipment mentioned above.

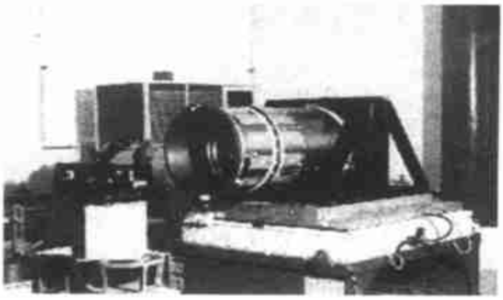
6　Space environment simulation experiment

Before the launch of the SORS, various kinds of simulation experiment have to be done on land to make sure the normal operation of SORS in the space environment.

For the force environment, we used the 9-ton electromagnetic oscillation stand purchased from UK and another home made D-600 type shown in Fig. 16.



(a) 600 kg electromagnetic oscillation stand

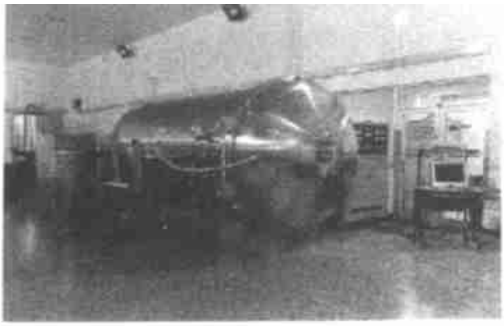


(b) 9 t electromagnetic oscillation stand

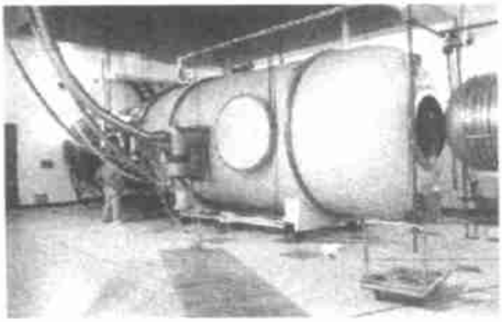
Fig. 16　The mechanic environment-testing lab

For thermal environment test, we built a thermal circulation setup shown in Fig. 17 (a) which has effective volume of Φ2 × 2.5 m, tightly sealed, filled with dried nitrogen, and temperature range of -60~ + 100 ℃.

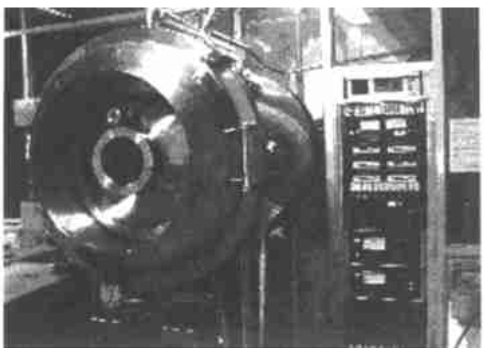
For thermal vacuum environment test, we built a thermal vacuum chamber shown in Fig. 17 (b) which has effective volume of Φ2.5 × 5.5 m, temperature range of − 173~ + 100 ℃, and ultimate vacuum pressure of 1.3×10^{-6} Pa.



(a) The Φ2× 2. 5 m thermal circulation setup

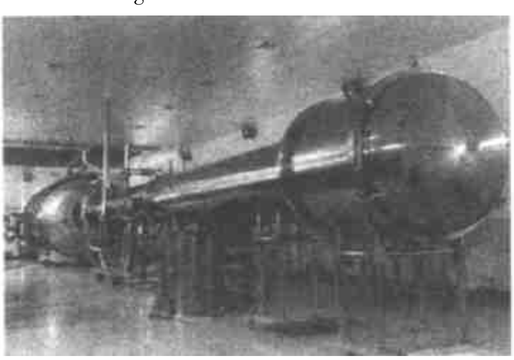


(b) The Φ2. 5× 5. 5 m thermal vacuum chamber



(c) The Φ0. 8× 1 m thermal vacuum chamber

Fig. 17 The thermal circulation and thermal vacuum environment testing lab



(a) The 20 m collimator and thermal vacuum chamber

(b) The 26. 5 m long air bearing isolation table

Fig. 18 The thermal balance and thermal-optics testing lab

For thermal optics environment test, we built a compatible vacuum collimator with a focal length of 13 m and 20 m, aperture size of Φ650 mm and Φ1 m, which can be pumped down together with the thermal vacuum chamber to the level of 1×10^{-4} Pa. The chamber and the 20 m collimator shown in Fig. 18(a) are put on the same 26. 5m long air-bearing isolation table shown in Fig. 18(b) to ensure the thermal optics environment testing.

We have carried out the thermal balance and thermal optics experiments for the whole SORS system using the setup above. The focal plane location of the camera on satellite was determined under the simulated space environment. The MTF under different temperature and pressure was also measured to make sure that the thermal control is effective and the SORS image resolution can meet the requirement in space environment by using these equipments mentioned above.

In summary, the state of the art SORS system has been successfully done in less than a decade at our institute. The institute has become the primary base for the SORS research and development with manufacturing and experimental capability.