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Science objectives and technology developments for ELTs in Japan

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Abstract. The future planning working group of the optical and infrared astronomy community of Japan completed its two-year study to yield a concrete plan for ground based telescopes and space missions for the coming decades. The R&D issues towards the realization of extremely large telescopes reported in this paper include a novel optical design, development of new ceramic mirrors, high precision grinding approach to reduce the involved cost and time for fabricating aspheric segmented mirrors, and conceptual studies of instruments.

The present paper is essentially a slightly updated version of the paper presented in the workshop "Instrumentation for Extremely Large Telescopes" held at Ringberg Castle, Bavaria, 25-29 July 2005.

Keywords. Telescopes; Techniques: ceramic segment mirror, high precision grinding, instrumentation.

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1. Introduction

The National Astronomical Observatory of Japan (NAOJ) formed an Extremely Large Telescope (ELT) Project office in April 2005. We have now 7 members and the present author serves as the head of the office.

1.1. *Future Planning Working Group*

The optical and infrared astronomers community (GOPIRA) decided in 2002 to organize an ad hoc working group to make an intensive study to draw its future plan for

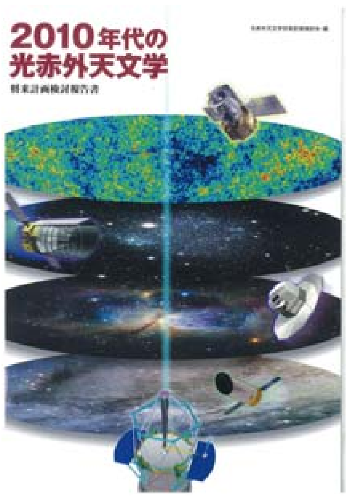

Figure 1. The cover page of the booklet compiled by the Future Planning Working Group.

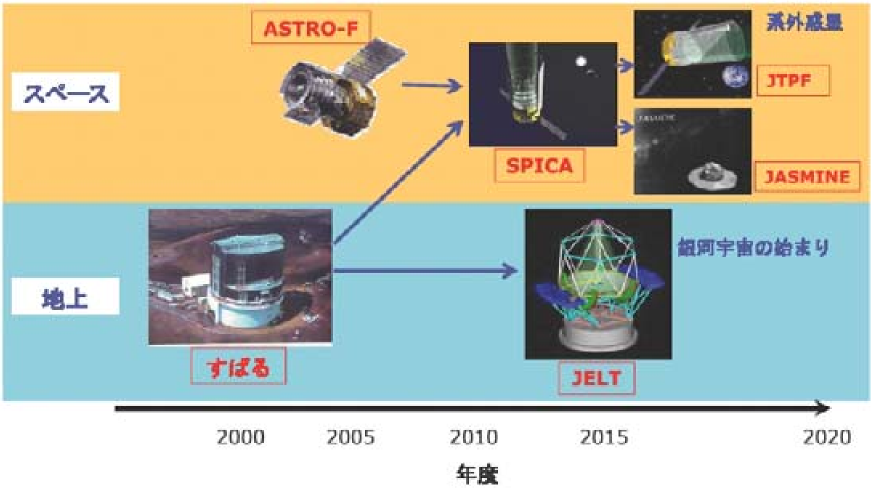

Figure 2. The recommended roadmap for ground based and space missions for the optical/infrared astronomy community of Japan towards 2010.

Table 1. Baseline concept of JELT

M1	F/1.5, segmented 30m
Segment material	Glass/Ceramic
Optical system	Three aspheric mirror system
Foci	two (or four) Nasmyth stations
FoV	10 arcmin radius
Wavelength range	Optical to Near Infrared
Instruments	Opt Spectrograph, IR Spectrograph, Cameras..
Enclosure	50m radius

optical and infrared astronomy. This future planning working group (FPWG: chaired by M.Iye) organized three subgroups on : science objectives, space missions, and ground-based projects. These subgroups concentrated their efforts to materialize the future plans and the outcome was reported to the community on several occasions. The final products in two booklets (Fig. 1) were forwarded to NAOJ and ISAS (Institute of Space and Astronautical Science) of JAXA (Japan Aerospace eXploration Agency) for further promotion (Iye 2004, FPWG 2005). The plan envisages a 30m JELT project, which will be described in more detail later, as the most urgent future plan for the ground based optical and infrared astronomy and also the SPICA mission, a 3.5m mid-infrared space telescope mission as the most beneficial space mission to complement the JWST. The SPICA mission fills the wavelength gap between JELT and ALMA (Fig. 2). The National Committee for Astronomy of the Japanese Academy of Sciences reviewed these plans and issued a recommendation to promote the plan.

Table 2. Some R&D activities for JELT

ZPF segment	Taiheiyo Cement/Japan Ceratech/NAOJ
High Precision Grinding Machine	Nagase Integrex/Nagoya Univ./Kyoto Univ./NAOJ
Optical design	Nariai and Iye

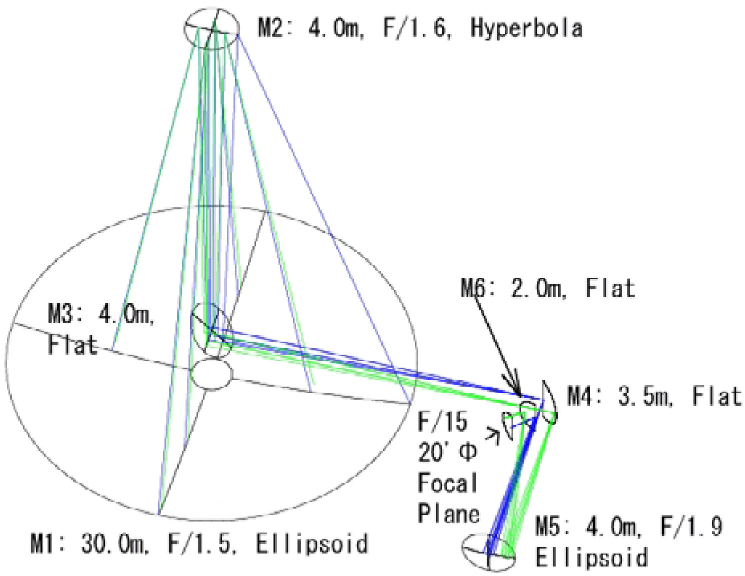

Figure 3. Optical layout of the 3 aspheric mirror system. Only one side of the two semi-circular focal positions on one of the Nasmyth platform is shown.

1.2. *Ground based Large Telescope Working Group*

The ground based large telescope WG† set the baseline concept for Japan's Extremely Large Telescope (JELT)(Iye 2004b). Some of the basic parameters are shown in Table 1. Considering the huge budgetary scale to promote the JELT project, the WG regards it highly desirable to seek for practical international collaboration. The collaboration should be made, desirably, from the concept design phase through construction and into operation phase with full exchange of information.

The ground WG initiated a survey of possible Japanese industrial expertise that might be useful for realizing the ELTs at modest cost. Table 2 shows the related areas of research and development under way or identified to be pursued. The status of the R&D will be described separately in the following sections.

2. Three aspheric mirror optical design

Nariai and Iye(2005) designed an optical configuration employing three aspheric mirrors to remove aberrations for providing a wide, flat field of view, up to 10 arc minutes in radius. Fig. 3 shows the proposed optical layout. The f/1.5, 30m ellipsoidal primary

† http://www.ioa.s.u-tokyo.ac.jp/elt/; only Japanese page is available for the moment

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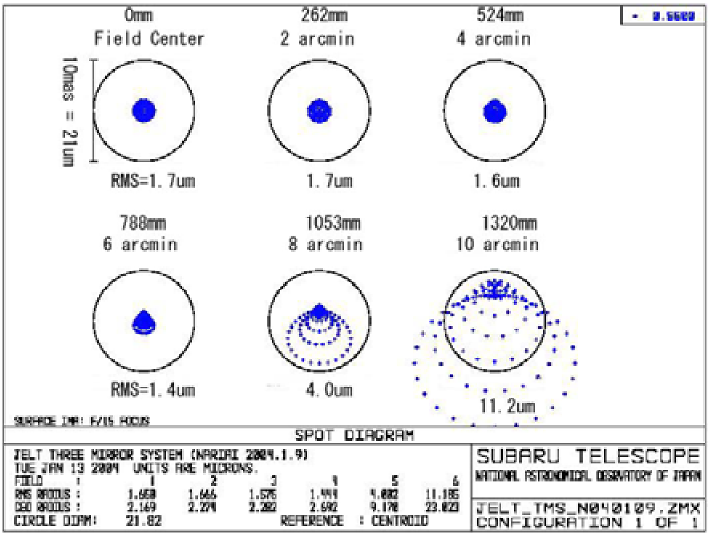

Figure 4. The spot diagrams showing the diffraction limited imaging capability of the three mirror system.

mirror consists of 798 concentric fan-shaped segments in 14 rings. The 4m hyperboloidal secondary and the 4m flat tertiary mirror produce a pseudo image plane at the Nasmyth platform, which is re-imaged by the fifth ellipsoidal mirror to give the final flat focal plane without aberration. Due to the beam vignetting, only a semi circular FoV is provided on one arm. At the very center of the field, a maximum of 50% of light is vignetted but the vignetting fraction is rapidly reduced away from the center of the field. One can add another arm to restore the remaining semi circular FoV. By turning the tertiary mirror, one can have two similar arms on the other side of the Nasmyth platform providing in total four laboratory spaces for huge ELT instruments.

Fig. 4 shows the spot diagrams of this optical system showing the diffraction limited imaging quality out to 8 arc minute in radius. The detailed layout of the Nasmyth platform with fourth to sixth mirrors and the final focal plane is shown in Fig. 5. The structure is based on truss frames and light weighted in comparison with the scaled versions of conventional telescope structures. Actual layout incorporating Atmospheric Dispersion Correctors must be made. In fact, it must be reminded that with much sharper images attainable with advanced adaptive optics for an ELT, the requirement for the atmospheric dispersion correction becomes a prohibitively severe condition to achieve.

3. Research and development on segment fabrication

3.1. *Zero-expansion Pore-Free Ceramics (ZPF)*

A consortium of NIHON CERATEC (http://www.ceratech.co.jp) and Taiheiyo Cement Corporation (http://www.taiheiyo-cement.co.jp/index.html) is developing a Zero-expansion Pore-Free ceramic (ZPF) for use, for example, as high precision zero-expansion stage for semi-conductor processing. By adjusting the fraction of SiC, Si_3N_4, etc. to mix in LAS(Li-Al-Si-O) powder to sinter, one can control the thermal expansion coefficient (CTE) to be close to zero at desired temperature. The residual CTE at 0°C is about 10 ppb.

Table 3 shows the physical characteristics of various candidate materials for mirror segments, e.g. CFRP (Carbon Fiber Reinforced Plastic), CMC (Ceramic Material

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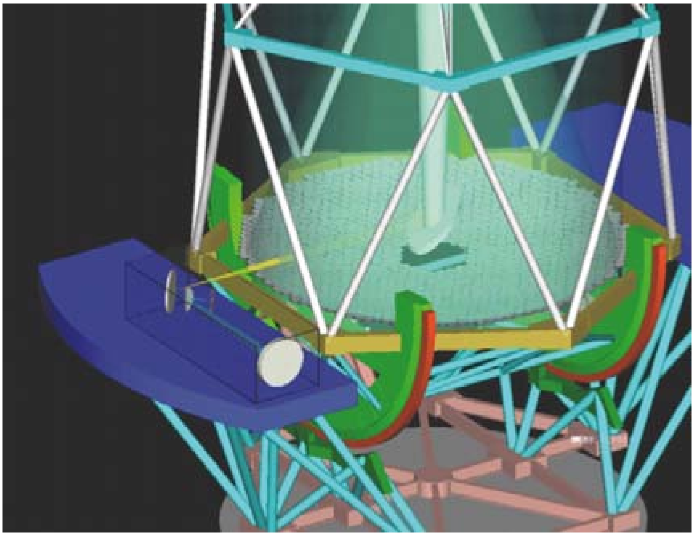

Figure 5. CAD drawing of the Nasmyth area.

Table 3. Physical parameters of materials for mirror segments.

Parameter	Symbol	Unit	CFRP	CMC	Glass	ZPF
Elastic modulus	E	GPa	120	400	90	150
Bulk density	ρ	g/cm^3	1.5	2.65	2.53	2.54
CTE	α	ppm/K	0.03	2.6	0.02	0.02
Thermal conductivity	Λ	W/K·m	50	125	1.6	5.3
Specific heat		J/kg·K	-	-	820	800
Bending strength		MPa	800	175	80	240
Roughness rms		nm		7.4	1	4
Stiffness/mass	E/ρ		80	150	35	60
Thermal stability	Λ/α		1700	50	80	260

Composite), Glass (Zerodur), and ZPF (Zero-expansion Pore Free ceramics). ZPF has a lower CTE compared to CMC, a higher elasticity and a higher bending strength than glasses. The material can be ground and polished. Thermal conductivity larger than the one of glasses is another favorable characteristics for mirrors. It can also be cemented with special zero-expansion cement, and can be light weighted by forming hollow structure before sintering. Forming the surface into a sphere before baking is also feasible to reduce the amount of grinding work. Taiheiyo Cement made an in–house experiment to polish a $200 \times 25 \times 25$mm rod and demonstrated that the residual surface error can be made as small as $1/30\ \lambda$. They also examined long-term stability of the finished surface as shown in Table 4. The surface does not show secular changes even after applying a thermal load up to 250°C. NAOJ also made an independent thermal cycle test using an

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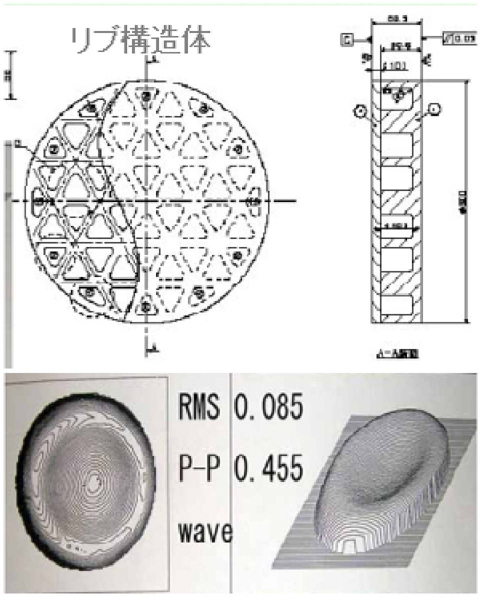

Figure 6. Light weight structure of a 30cm spherical ZPF mirror and its error figure.

optical interferometer to monitor the surface shape change over [0°C – 50°C] thermal cycles but found no significant deformation.

NAOJ obtained a few circular disks of 100mm diameter for test polishing and aluminizing in 2003. The spherical surface was generated at NAOJ by polishing, with a residual error figure of 0.1 wavelength and a surface roughness around 10 nm rms.

Table 4. Long-term stability of the ZPF surface

Event and Elapsed time	Surface error (λ)
As polished	0.045
1.5 year later before heating	0.048
after heated to 250°C	0.050
2.0 year later	0.052
2.5 year later	0.042

Encouraged by these initial positive results, we made a light weighted 30cm disk with a 4cm honeycomb rib structure plus 1cm thick face plates on both sides. Weight reduction by about 30% was achieved in this sample (Fig. 6). This light weighted ZPF disk was then ground and polished to form successfully a spherical mirror at NIKON, with a residual rms error less than 0.085 wavelength (Fig. 6).

The currently available furnace at NIHON CERATEC can sinter up to 80 cm × 50 cm ZPF blanks. To enable sintering a ZPF blank as large as 100 cm × 100 cm in size, some research and developments are necessary because the temperature range within which the ZPF compound is sintered to be a ceramic is only ±3 deg and a strict uniformity of temperature is required to sinter a large piece. If there is a temperature inhomogeneity

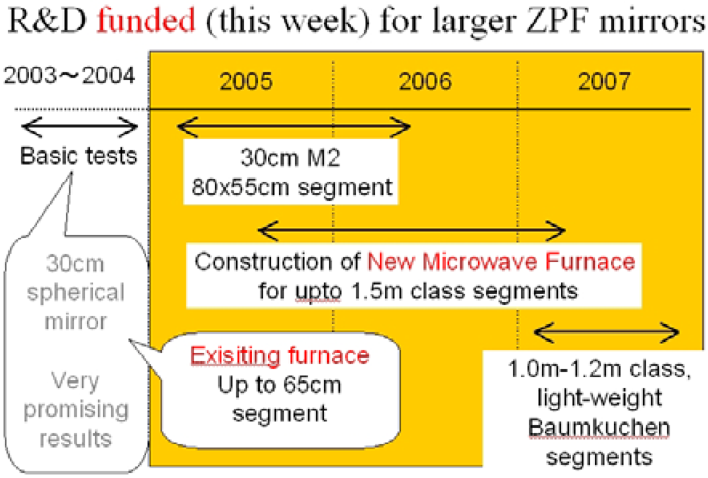

Figure 7. Schedule for manufacturing a new microwave furnace to sinter larger ZPF blanks.

exceeding this range, ZPF blanks can break due to the internal stress during the sintering process. The time profile to raise the furnace's temperature should also be strictly controlled.

To ensure a homogeneous temperature distribution and a gradually smooth temperature raising profile, a doubly insulated isothermal sintering furnace, where the ZPF compound to be sintered and the surrounding wall of the furnace are maintained in isothermal conditions, is designed by Prof. Motoyasu Sato at National Institute for Fusion Science. Rotating metal fans to deflect microwaves to heat the wall and the ZPF compound are incorporated uniformly in isothermal conditions.

The consortium received a research and development grant from the Japanese Science and Technology Agency (JST) to develop a new, large isothermal microwave sintering furnace for baking larger pieces of ZPF up to 1.2m square. This new furnace is under construction. Fig. 7 shows the time table of this R&D and the first ZPF blank of 100 cm $\times$ 100 cm would be sintered towards the end of 2006.

3.2. *High precision grinding machine*

The expertise of Nagase Integrex (http://www.nagase-i.jp/new_top/html/top/tope.htm) in their manufacturing of high precision grinding machining facilities attracted the interest of the ground WG. They achieved smooth driving of the work stage, by means of integrated hydrostatic bearings and precision drive mechanisms, approaching the nm level servo control. Another smart device they developed is a mechanism to realize real time balancing of the spinning head of the grinding tool. With these methodologies, coupled to a numerical computer (NC) control under a strictly controlled thermal environment and isolation of vibration, their grinding machine opens up a new possibility to grind out a hyper smooth surface purely by a NC process. In fact, an aspheric Schmidt plate of the FMOS instrument of the Subaru Telescope was ground by this type of machine to sub-micron precision for use in transmission mode. Although the final polishing is still necessary for generating the mirror surface, employing this pre-grinding process will significantly shorten the pre-processing time required and hence would be useful in reducing the manufacturing cost.

To see the potential of this method, we experimented NC grinding of our 10cm ZPF disks into a spherical surface first at Yamagata Research Institute of Technology where a

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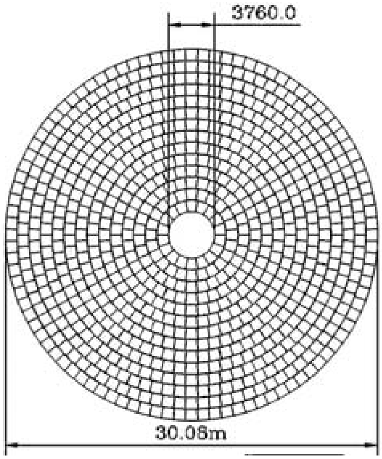

Figure 8. JELT segment configuration. A total of 798 segments, about 1m × 1m in size, are configured in 14 concentric rings to form a 30m mirror. Note that in this configuration, we need only 14 different aspheric shapes in contrast to the 123 different hexagon shapes required for the 738 segment concept of the TMT.

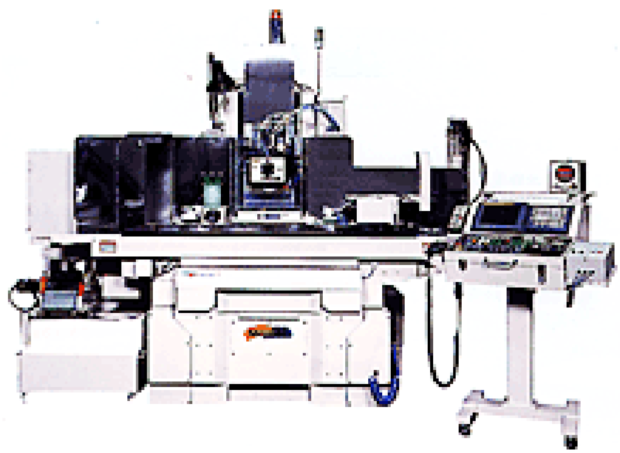

Figure 9. Nagase Integrex ultra high precision grinding machine.

Nagase's new NC grinding machine with 4 controlled axes, operated in a suitably maintained environment, has just been installed. Nagoya's University group led by Prof. S. Sato brought in an optical interferometer to measure the ground surface in situ. Although this experimental NC grinding was the "first cut" of this machine, grinding the rotating ZPF surface with a whetstone of grit #3000 by running the grinding head at 30mm s^{-1} across the surface with 0.1mm step to NC generate a spherical figure of radius of curvature 333mm yielded a surface with a peak-to-valley surface error as large as 5.6μm. It was found that the error profile reflects almost exactly the shape error of the grinding disk tool. By controlling the shape error of the grinding disk, we expect to generate a surface with an error at the 1 wavelength level.

The next experiment to achieve a spherical mirror surface was to grind the ZPF blank in a raster scan mode without rotating the blank. Establishing the operational parameters to achieve this mode to generate any non rotationally symmetric aspheric surface is a key issue for NC grinding. Our first attempt in this mode to generate a spherical surface

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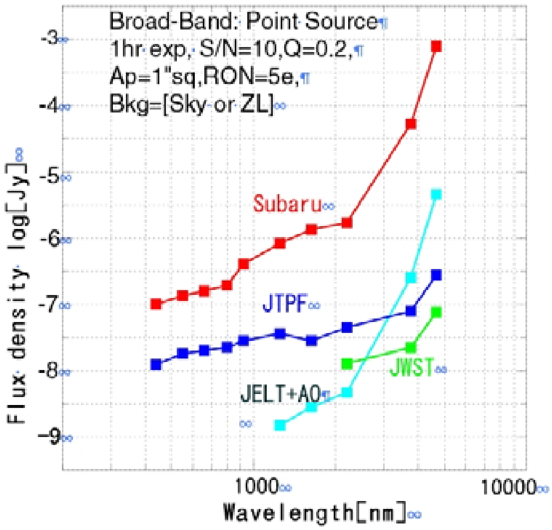

Figure 10. Limiting sensitivity of JELT and other major facilities for imaging observations of point sources.

has shown a few areas where further optimization appear necessary, e.g., controlling the shape error of the dressing tool, coordination of moving the stage and the dressing head, measurement facility to monitor the surface at a scale corresponding to the grinding pitch, and a maneuvering process to feed back the local grinding surface error.

In 2005, we are planning to produce a 33cm aspheric ZPF secondary mirror for a 1.5m telescope at Hiroshima University. Nihon Ceratec plans to sinter a honeycomb structure ZPF blank with 50% weight reduction with its front surface roughly in spherical shape. Nagase Integrex is planning to grind the front surface to a $\sim 1\mu$m shape error level. Nikon is planning to give final polishing to a 1/12 wavelength level. If the entire process is completed successfully, this would produce the first ZPF mirror of practical use on a telescope. We are planning to verify its optical performance for astronomical observations and see if there is any potential problem with this new material that we are not aware of at present.

In 2006, we are planning to produce a 1m class ZPF aspheric segment sagged roughly to the final curved surface and then grind its surface to generate a 1λ level. If this turns out to be practically useful to produce an aspheric surface, with optical quality, for 1m-class material in much shorter time than was needed for the conventional method, this would revolutionize the segment production's process.

4. Instrumentation

A study to evaluate the limiting magnitudes of Imagers and Spectrographs for ELT was made and the results are compiled in the 2010's decadal report for Optical/Infrared Astronomy. A few groups are developing conceptual designs of some instruments for ELTs based on the expertise developed around the instruments for the Subaru Telescope. Instruments under preliminary concept studies are, (1)a High Dispersion Spectrograph, (2) a High Resolution Imager/Spectrograph with Adaptive Optics, (3) a Mosaic of Modular Infrared Spectrographs, (4) Multiple Mid-Infrared Camera/Spectrographs, and so on.

5. Conclusions

NAOJ formed in April 2005 an ELT project office for the promotion of ELT related activities. A two-years study of the community working group to layout the future plan both for the ground based and space missions for optical and infrared astronomy were compiled into a pair of report booklets and the plan got recommendation for further promotion from the Council for Astronomy. The ELT project office is making concentrated efforts to develop new ceramic mirrors using a high precision grinding method to verify a novel approach to mass produce aspheric segmented mirrors at reduced cost and time. The WG is tentatively drawing a 30m ELT plan of its own but is open for promoting international collaboration to construct a 30m or even larger ELT.

Acknowledgements

The author is grateful to members of the Future Plan Working Group for their intensive studies that were distilled to form the content of the present report. Optical design was made by Kyoji Nariai of Meisei University and the present author. Noboru Itoh and George Oshima of Mitsubishi Electric Corporation made CAD and FEM studies of the telescope structure. Special thanks go to Masashi Otsubo and Kenji Mitsui at the Advanced Technology Center of NAOJ for polishing ZPF pieces. Thermal cycling tests of ZPF were carried out by Naoki Kohara of Tokyo University. Figures 4 and 5 were kindly provided by Mamoru Ishii of Taiheiyo Cement Corporation and Shiro Moriyama of NIHON CERATEC. Motoyasu Sato of the National Institute for Fusion Science developed the plan for enabling the sintering of larger ZPF blanks by introducing the isothermal microwave heating furnace. Stimulating discussions with Masao Yamaguchi and Yukiyasu Nagase of Nagase Integrex Co., and Shuji Sato of Nagoya University are also greatly acknowledged. Zen-ei Tanaka, Ryo Kaneda, and Mitsutaka Watanabe of the Yamagata Research Institute of Technology cooperated in making NC test grindings of 10cm ZPF pieces. Shuji Sato, Mikio Kurita, Masaru Kino and Kaori Fukumura of Nagoya University constructed an optical interferometer to measure the ground surface of the mirror in site. Kentaro Motohara of Tokyo University helped to organize the WG activity. Finally as a cautionary remark, it is important to note that the present contribution is biased by the author's personal view and not endorsed by any authority.

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