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**Abstract:** The status of the research and development in Japan toward the realization of extremely large telescopes is reported. The future planning working group of the optical and infrared astronomy community completed its two-year study to yield a concrete plan for ground based telescopes and space missions for the coming decades. Reported in the present paper are the basic concept of an extremely large telescope and some related specific issues under development, including 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, conceptual studies of instruments, and other engineering activities.

**Keywords:** 30m telescope, ceramic segment mirror, high precision grinding, instruments

## 1. INTRODUCTION

The National Astronomical Observatory (NAO) formed Extremely Large Telescope (ELT) Project office from April 2005.

### 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 optical and infrared astronomy. The author of the present paper was nominated to serve as the chair of this working group. The future planning working group (FPWG) organized three subgroups on : science objectives, space missions, and ground-based projects. These subgroups made concentrated effort to materialize the future plans and the outcome was reported to the community on several occasions. The final product 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. 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 and also filling the wavelength gap between JELT and ALMA (Fig. 2). The National Committee for Astronomy of Japan Academy of Science reviewed these plans and issued a recommendation to promote the plan.

### 1.2. Ground based Large Telescope Working Group

Ground based large telescope WG (<http://www.ioa.s.u-tokyo.ac.jp/elt/>; only Japanese page is available for the moment) set the baseline concept for Japan Extremely Large Telescope (JELT) as shown in Table 1. However, considering the possible necessity to promote JELT project under a framework of an international collaboration, the WG considers it highly desirable to seek for practical international collaboration. The collaboration should be made from the concept design phase to the basic research and development programs 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.

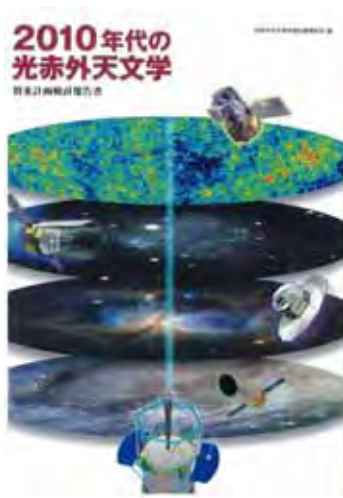


Figure 1. The cover page of the booklet compiled by the Future Planning Working Group.

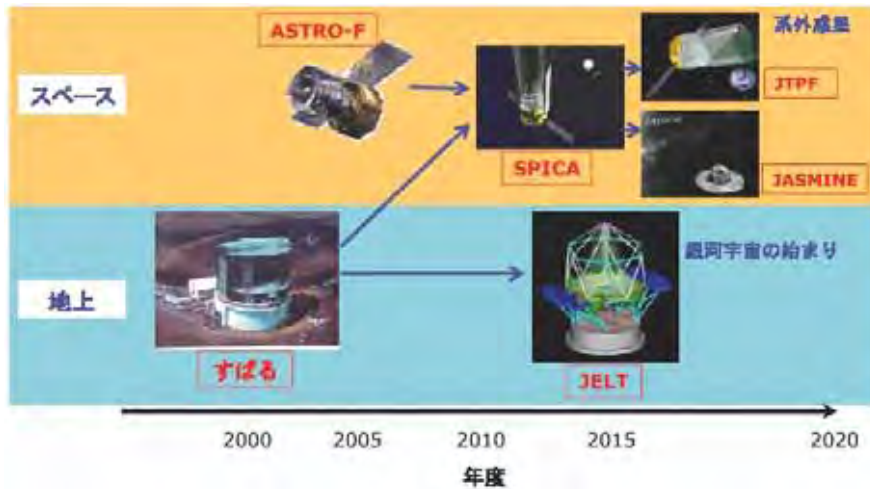


Figure 2. The recommended roadmap for ground based and space missions for the optical/infrared astronomy community of Japan towards 2010's.

## 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 minute in radius. Fig. 3 shows the proposed optical layout. The F/1.5, 30m ellipsoidal primary 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 vigneting, only a semi circular FOV is provided on one arm. At the very center of the field, the maximum of 50% of light is vigneted but the vigneting 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 similar two arms on the other side of the Nasmyth platform providing in total of four laboratory spaces for huge ELT instruments.

**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

**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

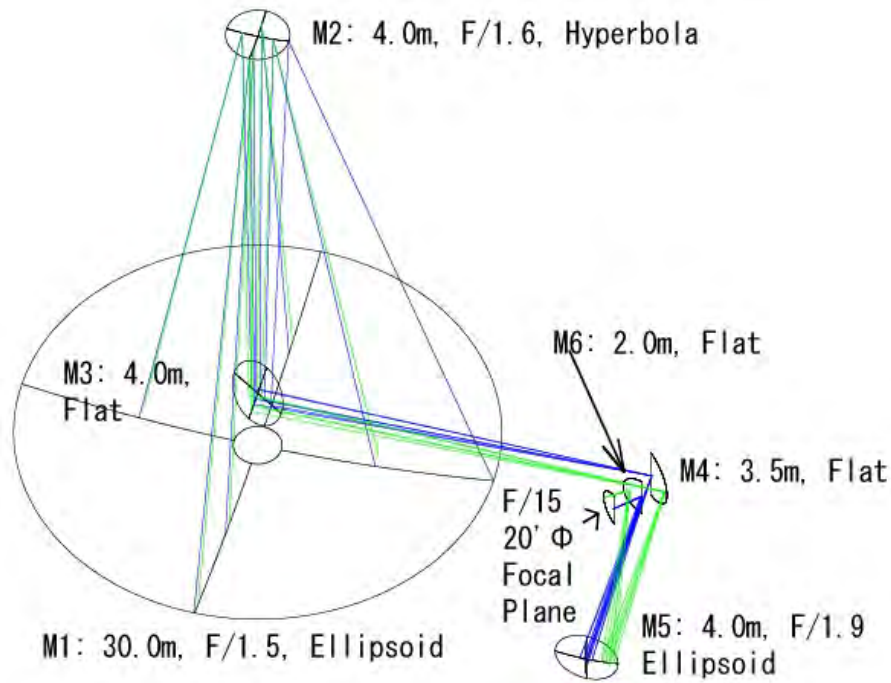
Fig. 4 shows the spot diagrams of this optical system showing the diffraction limited imaging quality out to 8 arc minute in radius. The detailed layout of the Nasmyth platform with fourth to sixth mirrors and the final focal plane is shown in Fig. 5. The structure is based on truss frames and light 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)

NIHON CERATEC (<http://www.ceratech.co.jp>) and Taiheiyo Cement Corporation (<http://www.taiheiyo-cement.co.jp/index.html>) are 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 to be close to zero at desired temperature. The residual CTE at  $0^\circ C$  is about 10 ppb.

Table 3 shows the physical characteristics of various candidate material for mirror segments, e.g. CFRP (Carbon Fiber Reinforced Plastic), CMC(Ceramic Material Composite), Glass (Zerodur), and ZPF (Zero-expansion Pore Free ceramics). ZPF has a lower CTE compared to CMC, a high elasticity and a high bending strength than glasses. The material can be ground and polished. Thermal conductivity larger than that for 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. 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

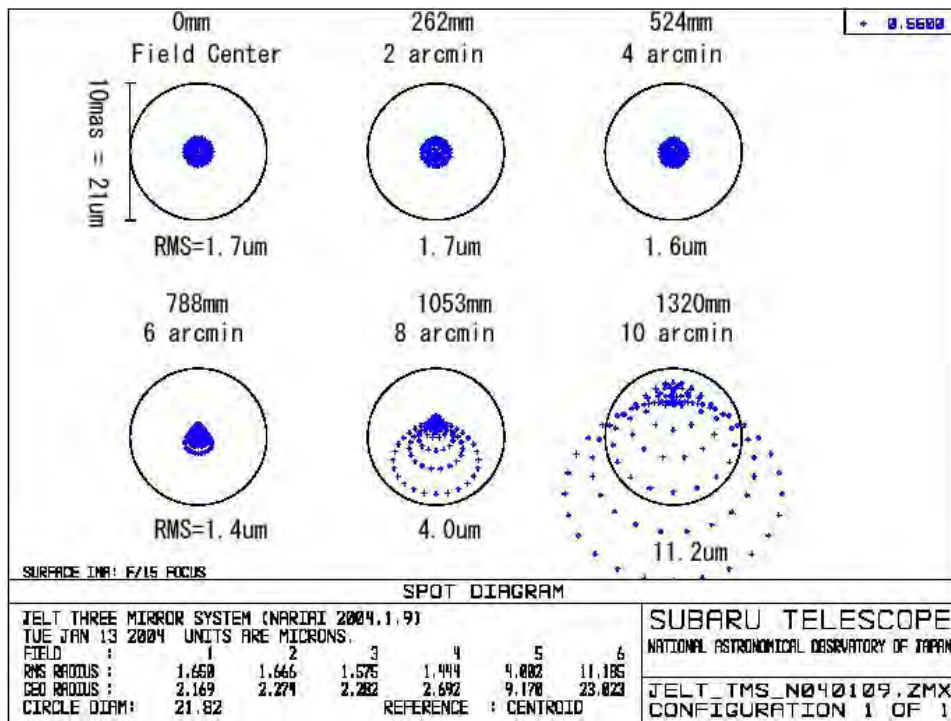


**Figure 3.** Optical layout of the 3 aspheric mirror system. Only one side of the two semi-circular focal positions on one of the Nasmyth platform is shown.

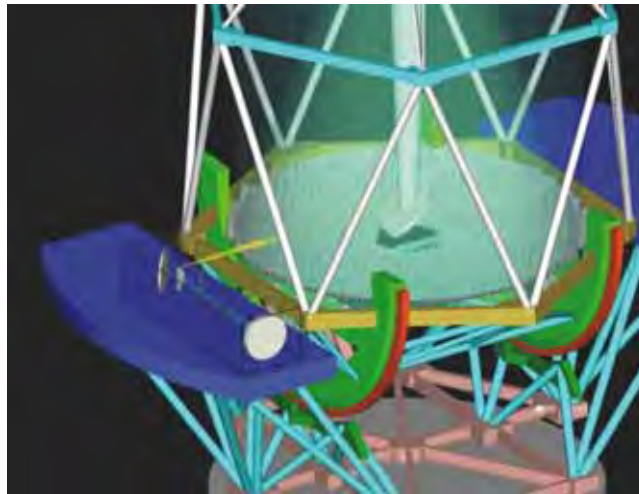
**Table 3.** Physical parameters of materials for segment mirrors

Parameter	Symbol	Unit	CFRP	CMC	Glass	ZPF
Elastic modulus	E	GPa	120	400	90	150
Bulk density	$\rho$	$g/cm^3$	1.5	2.65	2.53	2.54
CTE	$\alpha$	ppm/K	0.03	2.6	0.02	0.02
Thermal conductivity	$\Lambda$	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	$E/\rho$		80	150	35	60
Thermal stability	$\Lambda/\alpha$		1700	50	80	260

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 change even after applying a thermal load up to  $250^\circ C$ . NAOJ also made an independent thermal cycle test using an optical interferometer to monitor the surface shape change over 0 deg – – 50 deg thermal cycles but found no significant deformation.



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



**Figure 5.** CAD drawing of the Nasmyth area.

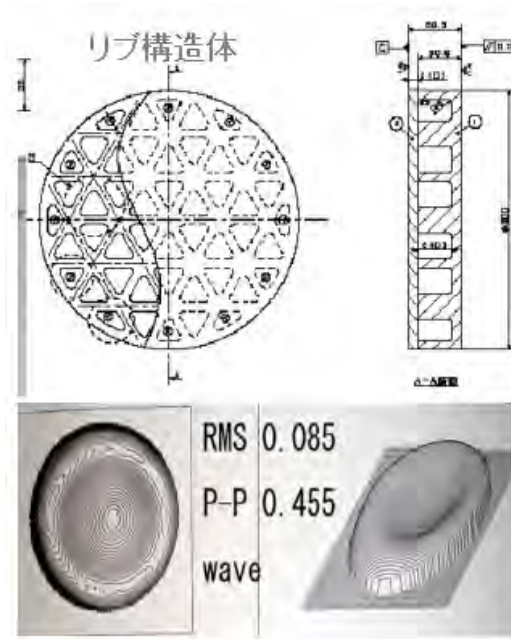
NAOJ obtained a few 100 mm circular disk for test polishing and aluminizing in 2003. The spherical surface was generated at NAOJ by polishing with the residual figure error of 0.1 wavelength level and the surface roughness around 10 nm rms.

Encouraged with these initial positive results, we made a light weighted 30cm disk with a 4cm honeycomb rib structure plus 1 cm 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

**Table 4.** Long-term stability of the ZPF surface

Event and Elapsed time	Surface error ( $\lambda$ )
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

and polished to form a spherical mirror by an experienced optical company successfully with a residual rms error less than 0.085 wavelength (Fig. 6).



**Figure 6.**

The currently available furnace at NIHON CERATEC can sinter up to 80 cm x 50 cm ZPF blank. To enable sintering a ZPF blank as large as 100 cm x 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  $\pm 3$  deg and a strict uniformity of temperature is required to sinter a large piece. If there is a temperature inhomogeneity exceeding this range, ZPF blank can be broken due to the internal stress during the sintering process. The time profile to raise the furnace temperature should also be strictly controlled.

To ensure homogeneous temperature distribution and gradual 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 the isothermal condition, is designed by Prof. Motoyasu Sato at National Institute for Fusion Science. The rotating metal fans to

## R&D funded (this week) for larger ZPF mirrors

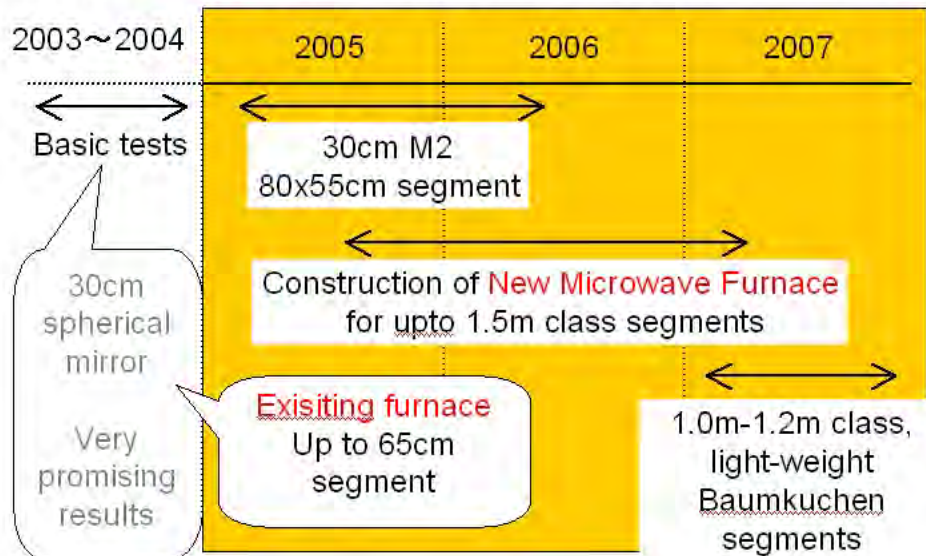


Figure 7.

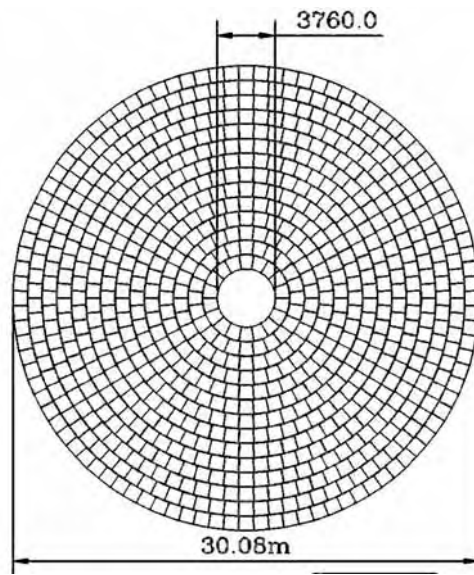
deflect the microwave to heat the wall and the ZPF compound uniformly in isothermal condition are incorporated.

The consortium received a research and development grant from the Japan 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. Some basic tests and experiments to characterize the design specification for new furnace are under way. Fig. ?? shows the time table of this R&D and the first ZPF blank of 100 cm x 100 cm would be sintered toward the end of 2006.

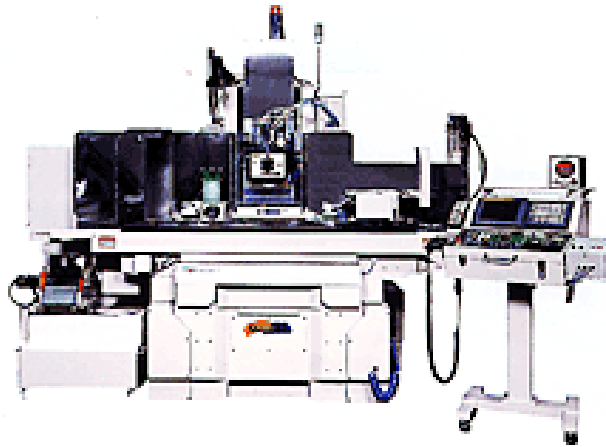
### 3.2. High Precision Grinding Machine

The expertise of Nagase Integrex ([http://www.nagase-i.jp/new\\_top/html/top/tope.htm](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 integrating hydrostatic bearings and precision drive mechanism, 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 methodology coupled with the 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 an NC process. In fact, the aspheric Schmidt plate of FMOS instrument of Subaru Telescope to be used in transmission was ground by this type of machine to sub-micron precision. 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 10 cm ZPF disks into a spherical surface first at Yamagata Research Institute of Technology where a Nagase's new NC grinding machine with 4 controlled axes operated at suitably maintained environment



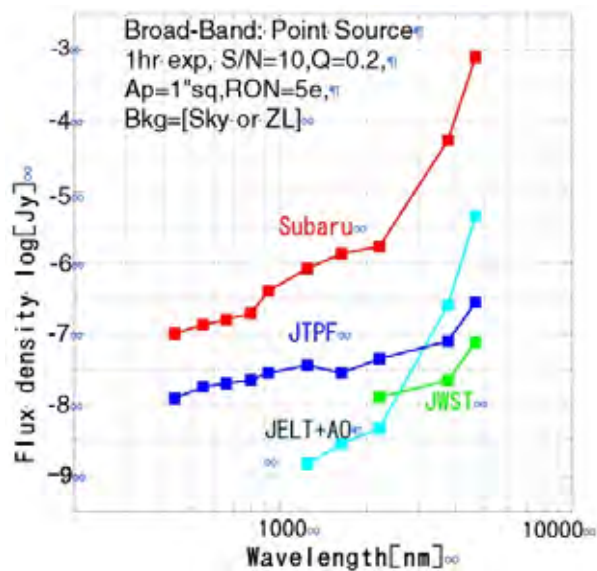
**Figure 8.** JELT segment configuration. A total of 798 segments, about 1m x 1m in size, are configured in 14 concentric rings to form a 30m mirror. Note that in this configuration, we need only 14 different aspheric shapes in contrast to the 160 different hexagon shapes required for 1080 segment concept of TMT.



**Figure 9.** Nagase Integrex ultra high precision grinding machine.

has just been installed. Nagoya 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 30 mm/sec across the surface with 0.1 mm step to NC generate a spherical figure of radius of curvature 333 mm yielded a surface with peak-to-valley surface error as large as  $5.6 \mu$ . It was found that the error profile reflects almost exactly the shape error of the grinding disk. By controlling the shape error of the grinding disk, we expect to generate a surface with an error at 1 wavelength level.

Next experiment of grinding to achieve a spherical mirror surface was to grind the ZPF blank in an raster scan mode without rotating the blank. Establishing the operational parameters to



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

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 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 33 cm 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 about  $1\mu$  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 and we would like 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 1m class ZPF aspheric segment sagged roughly to the final curved surface and then grind its surface to generate  $1\lambda$  level. If this turns out to be practically useful to produce an aspheric surface for 1m-class material with optical quality in much shorter time than was needed for the conventional method, this would revolutionize the segment production 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 the Optical/Infrared Astronomy. A few groups are developing conceptual design of some instruments for ELT based on the expertise developed around the instruments for Subaru Telescope. Instruments under preliminary concept studies are, (1)High Dispersion Spectrograph, (2) High Resolution Imager/Spectrograph

with Adaptive Optics, (3) Mosaic of Modular Infrared Spectrographs, (4) Multiple Mid-Infrared Camera/Spectrographs, and so on.

## 5. SUMMARY

NAOJ formed in April 2005 an ELT project office for the promotion of ELT related activities. A two-year studies of the community working group to layout the future plan both for the ground based and space missions for the 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 high precision grinding method to verify a novel approach to mass produce aspheric segmented mirrors at a 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.

## ACKNOWLEDGMENTS

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 are to Masashi Otsubo and Kenji Mitsui at the Advanced Technology Center of NAOJ for polishing ZPF pieces. Thermal cycling test of ZPF was 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 National Institute for Fusion Science developed the plan for enabling the sintering of larger ZPF blanks by introducing the isothermal microwave heating furnace. Stimulating discussion 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 Yamagata Research Institute of Technology cooperated in making NC test grinding of 10 cm 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 on the author's personal view and not endorsed by any authority.

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