**Evaluation of the Subaru Telescope and the Extremely Large Telescope Project**
**Report by the International Review Committee**

March 31, 2008

## Executive Summary

In its eight years of scientific operation in open use the Subaru Telescope has developed into a world-leading facility in ground-based astronomy. Outstanding contributions to the advancement of modern astrophysics have been made with observational data taken with Subaru. A large number of refereed scientific papers based on Subaru observations and covering a wide range of astronomical science is published every year. The generally high citation rate of these papers indicates world-wide recognition of the Subaru scientific accomplishments. The Review Committee is deeply impressed by this story of success. Subaru delivers a superb image quality and is equipped with first-rate instruments, some of them unique. Very competent and dedicated staff operate and maintain the telescope and its instruments efficiently. A vibrant community of astronomers makes excellent use of the unique science opportunities provided by Subaru.

The future plans for the Subaru Telescope are ambitious and bold. They keep the momentum obtained from the present success and envisage an exciting scientific future for Japanese astronomy. The committee is very supportive of these plans.

There have been remarkable developments over the review period in Japanese preparations for participation in an Extremely Large Telescope. In the early years of this period an extensive set of design studies was undertaken towards a 30m JELT based on the `baumkuchen' primary mirror configuration. This work, led by Iye, established a strong basis for the scientific, technical and industrial participation of Japan in an ELT project. The scale and cost of constructing a 30m telescope led to the project's decision in early 2007 to seek to join the California led Thirty Meter Telescope project should that telescope be sited on Mauna Kea. A major advantage of this approach is that *Japanese astronomers will gain access to the first ELT to be built*. The committee views this decision very positively and urges the Japanese community to use the full weight of its considerable influence to ensure that the TMT ***is*** built on Mauna Kea. This is now a matter of the highest priority and greatest urgency.

## 1. Introduction

In February 2008 Dr. Shoken Miyama, Director General of the National Astronomical Observatories of Japan (NAOJ), invited an international committee to review the achievements and activities of the Subaru Telescope and the Extremely Large Telescope Project (ELT). The committee was provided with a documentation prepared by the Subaru Telescope and ELT and explaining their activities since 2004. The documentation also contained a detailed self-assessment which is reviewed in this report.

The committee visited the Subaru Telescope on the summit of Mauna Kea, Hawaii, on 27 February 2008 and obtained information about the telescope and instrument operation. The review meeting was held on the two subsequent days, February 28 and 29, at the Subaru facility in Hilo. On the first day, following the opening remarks by the Vice-Director General Toshio Fukushima, the committee discussed the scope of the review in closed session, before Masahiko Hayashi, Director, Subaru Telescope, gave overview presentations of the Subaru activities. The meeting continued with science presentations from three astronomers representative for the Subaru users community and a lively discussion of the variety and wide range of results ensued. In addition, the committee met with a group of Subaru Junior Scientists to hear their frank opinions. This was followed by a tour of the Hilo Base Facility and the Imiloa Astronomy Center. Ample time was also set aside for discussion in closed session.

On the second day, the review focused on Subaru development activities with presentations by the Director, staff scientists and principal investigators with responsibility for the design and construction of major instruments. The presentations concluded with a detailed report on the ELT project. All the presentations were discussed intensively. The committee also interviewed a group of Senior Scientists to obtain additional information. Most of the second afternoon was spent in closed discussion in preparation for this report.

## 2. Subaru Telescope

The Subaru Telescope started regular scientific operation in open use in December 2000 and is now in its $8^{th}$ year of operation. The step from the 1.88-m telescope in Okayama to the 8.2-m Subaru Telescope at the summit of Mauna Kea, the best astronomical site in the world, has been an enormous scientific improvement for the Japanese astronomical community. It has also been regarded as a tremendous challenge in terms of technology development, operations and scientific use.

The Review Committee notes that the design, construction and now science operation of Subaru is a remarkable story of success. In a world of strong international competition with other 8-m to 10-m class telescopes such as the Keck Observatories, the ESO Very Large Telescope, and the Gemini Observatories the Subaru Telescope has made important and in many cases fundamental and outstanding contributions to the dramatic advancement of modern astronomical science. This is the result of an impressive amalgam of three components: a dedicated team of observatory staff provides a telescope, which delivers the best image quality in the world, advanced instruments, which are world-class and in some cases unique, and a vibrant community of scientists, which has made excellent use of this unique science opportunity. This is the result of careful strategic planning and consideration of the important new directions of astronomy.

## 2.1 Science Accomplishments

The scientific accomplishments of the Subaru Telescope are impressive and cover a wide range of astronomical science from the solar system, star and planet formation, stellar physics to extragalactic astronomy and cosmology. The many results obtained, some of them truly outstanding, are published in the world leading refereed journals. The number of publications in refereed journals has increased continuously. It is now at the high level of ninety publications per year, absolutely competitive with Keck and the ESO VLT. The number of citations of these publications is also high and comparable to those from these two competing observatories. These are clear indicators of the world-class science produced by the Subaru Telescope and its community of users.

A number of science projects carried out with Subaru have accomplished outstanding results. The surveys of the high-redshift universe with Suprime-Cam and follow-up spectroscopy have resulted in the detection of the most distant galaxy in the universe, a Lyman-alpha emitter at redshift $z = 7$, providing fundamental constraints on the theory of galaxy formation and the re-ionization of the universe. Equally, the multi-band deep imaging survey for such galaxies in a redshift range $z = 5.7$- 6.6 has for the first time led to an estimate of the star formation rate and to a measurement of the large scale filamentary structure of galaxies in the very early universe. In addition, the large number of objects found made it possible to measure the galaxy luminosity function indicating the effects of evolution and the incompleteness of re-ionization at $z = 6.5$. A similar survey for Lyman Break Galaxies at somewhat lower redshift ($z = 4$ to 5) detected ten thousands of such objects over a field of view larger than one degree producing for the first time an accurate and detailed study of the spatial distribution and luminosity function at this redshift. This is a fundamental test of the existing models of galaxy formation in a Cold Dark Matter dominated universe. At relatively low redshift ($z = 0.1$ – 1.0) the Subaru Suprime-Cam multi-color imaging survey of 500,000 galaxies combined with the HST COSMOS survey has revealed the three-dimensional distribution of dark matter in the universe for the first time. The Surprime-Cam study of the formation of galaxy clusters has revealed a filamentary structure spread over scales of 20 Mpc with a significant truncation in the star formation process even in galaxies very distant from the cluster cores. This important observation supports recent models of hierarchical structure formation in the universe.

There is no question that this vigorous exploitation of the unique capability of Suprime-Cam as a wide field imager for cosmological surveys is an outstanding success and has an enormous scientific impact. However, it is also important to note that these surveys have only been successful, because the Subaru Telescope has “workhorse-instruments” such as FOCAS available, which have enabled the spectroscopic follow-up observations. In addition, outstanding cosmological observations based on FOCAS alone have been carried out, such as the detection of the most distant Gamma-ray burst at $z = 6.3$. These data were used to determine the metallicity of the host galaxy and the degree of ionization in the surrounding intergalactic medium.

The observation of the high redshift universe and of galaxies at very large distances is not the only way to address key questions of modern cosmology. Equally important is the study of the archeological record of chemical composition of the oldest stars in the halo of our own galaxy, which reveals the nucleosynthesis signatures of the first generation of stars and provides constraints on the star formation process in the early universe. The quantitative spectral analysis of the most metal poor star carried out with the Subaru High Dispersion Spectrograph is an outstanding highlight, which has attracted worldwide attention. The very unusual chemical abundance pattern determined provides a unique opportunity to test the existing models of chemical evolution and supernova explosions. Similar work on somewhat less metal depleted objects to study the chemical enrichment in the universe through neutron capture in the s- and r-process is equally fundamental and important. The Review Committee is pleased to learn that the world experts have joined forces with the leading stellar spectroscopists in the Japanese community to use the Subaru Telescope and the ESO VLT jointly for these studies.

About a quarter of the Subaru observing time is used for the study of star and planet formation and the investigation of the solar system. This work has resulted in exciting results of outstanding importance. CIAO and IRCS have been used to reveal the complex structure in circumstellar disks. These observations are crucial for the understanding of the physical mechanism for planet formation in such disks. Mid-infrared observations carried out with COMICS have led to an analysis of the dust composition of debris disks demonstrating the formation of crystalline silicates and the radial variation of the chemical composition across the disk, a crucial observation to understand the formation of planetesimals.  Observations with Subaru and Keck have led to the discovery of a Saturn-like extra-solar planet, which has the same mass as Saturn but a much smaller radius and is the highest density gaseous planet ever detected. This detection favors a formation mode for planets, which starts from a solid core and then accumulates gaseous material.

A very important area of research in our solar system has been the search for small bodies using the wide field capability of Suprime-Cam. The study of the distribution of sizes of the main belt asteroids compared to near earth asteroids has shows that the former must be responsible for the "heavy bombardment" in the solar system in the period more than 3.8 Gyr ago, whereas the latter are responsible for younger impact events. It seems clear that the Moon is the result of a collision during the period of heavy bombardment.

Another important application of Suprime-Cam is the detection of more than 60 irregular new moons around Jupiter, Saturn, Uranus and Neptune, which are obviously asteroids captured by the gravitational field of the planets. The dynamical process leading to such captures is presently unknown. The existence of these objects is seen as an indication that important parts of the formation process of our solar system are still not well understood.

In summary, the Review Committee concludes that the science achieved with Subaru is at the world frontier level.

## 2.2 Telescope and Instrument Performance

With a superb median seeing of 0.6 arcsec at R and I bands over the full field of view of 30 arcmin Subaru continues to deliver the best image quality of the existing 8m class telescopes in the world. The Review Committee commends the Subaru staff to this remarkable accomplishment. It also documents the unique quality of Mauna Kea as an observatory site.

Down time averaged over the two 2007 semesters has been lower than 4% with 1.5, 1.9 and 0.5% related to telescope, instrument or software problems, respectively. These statistics are excellent and indicate a very effective, smooth and stable operation. Given the enormous challenges posed by the many Subaru instruments, the multi-focus readiness and the frequent and complex instrument changes, this can only be accomplished through the advanced robotic exchange system, which is unique.
Of course, it also requires the enormous dedication and pride of the support astronomers, day crew and instrument technicians.

The observatory operation is efficient and up to the highest standards.

## 2.3 Instrumentation

The Subaru Telescope is the only 8-m class optical and infrared telescope available to the Japanese astronomical community. In order to satisfy all the needs of the community, the suite of instruments is unusually large for one telescope. While this is definitely a challenge for instrument operation and maintenance, it has also opened a large variety of science opportunities, which would not have been available otherwise.

Many of the Subaru instruments are and have been unique. Suprime-Cam as a prime focus wide field imager is still without competition in the world and has revolutionized astronomy in many areas. CIAO was the leading coronographic adaptive optics imager, when it came on line, and COMICS has been the most efficient mid-infrared instrument at an 8-m class telescope. MOIRCS will continue in this tradition as the most advanced wide field infrared multi-object spectrograph with cooled slits and outstanding image quality of 0.18 arcsec over the whole field (best seeing size in FWHM). This instrument is at least two years ahead of the international competition and will enable outstanding science. The committee is impressed by the efficient and successful cooperation between the university team (involving PhD students and postdocs) responsible for the instrument and the Subaru observatory staff.

Other instruments such as FOCAS, HDS and IRCS, while not unique, compare extremely well in their performance and efficiency with competing instruments at Keck, Gemini and the ESO VLT. As “workhorses” they have made very important contributions to the Subaru science.

The Subaru instrument development has been innovative, comprehensive and well-planned. It is an outstanding accomplishment.

## 2.4 Operation, User Support and International Collaboration

The decision to build the Subaru Telescope on Mauna Kea in Hawaii was the most essential for the success of the Project. Not only did it provide with access to the best observatory site in the world, it also encouraged the Japanese astronomers to take on the challenge of world wide competition on the highest scientific level. The community of Subaru users in Japan has done this through the very successful initiation of inter-university collaboration, which built on the existing strengths and also activated and included many local university groups. Good examples are the contributions by the Kyoto group during the implementation and commissioning phase of the telescope and by the Tohoku group in the design, construction and test phases of MOIRCS. In addition, international collaborations were established, which proved to be very valuable and effective. The developments of Hi-CIAO, Hyper Suprime Cam and FMOS are excellent examples. As a result, many of the excellent scientific results have been obtained in Japanese inter-university or international collaborations. This has made Japanese ground-based astronomy world –wide competitive. It will be very important to continue and to expand this successful system of national and international collaboration in the future for the larger and even more ambitious missions to come.

Another advantage of building the Subaru Telescope overseas was to face the challenge of operating and collaborating within a different social and cultural environment and a different system of science support. This has been very successfully addressed by the development of special system, which employs supporting staff, engineers and technicians through the collaboration with the University of Hawaii and its Research Corporation (RCUH). This system of support has turned out to be inevitable for the present very efficient and smooth operation of the Subaru Telescope.

While the operation is smooth, efficient and very successful, the committee has realized that the workload on the staff is generally very heavy resulting in a situation in which it is difficult for them to accomplish progress with their own scientific work. It is important that this issue is recognized by the Subaru management and NAOJ. In the long run, competent users and instrument support can only be accomplished with junior scientists at the observatory who see a clear opportunity for scientific and professional development in their work for the observatory. It is, therefore, very important that operation budget and the support staff man power is kept at the appropriate level.

## 2.5 Future Plans

While the Subaru Telescope and its instrumentation have been scientifically very successful and competitive over the last eight years of operation, it is very important to keep these high standards and to remain at the forefront internationally. The competing large telescope projects in the world, Keck, Gemini and the ESO VLT, and their science communities have developed very ambitious plans for the 2$^{nd}$ generation instruments. It is important that Subaru after its excellent start keeps up the momentum it had gained. This might be a challenge for the Japanese community, as simultaneously with the development for the next generation of instruments the plans for a participation in a next generation Extremely Large Telescope have also become very concrete (see below). Careful planning will be needed to find the right balance of investment, to use the synergies between the two projects, and to identify new financial and human resources.

The most advanced next generation instrument is the laser guide star adaptive optics camera using a 188 element curvature sensor system. Combined with IRCS this will be an extremely powerful adaptive optics system with a very high Strehl ratio over a wide wavelength range from 1 to 5 microns. This new system will be extremely competitive and will facilitate first rate-science in star and planet formation studies, but also in extragalactic astronomy. To use the spatial resolution advantage of diffraction limited large telescopes has become a key area in modern astronomy. It is an important step for Subaru and its users' community to have again access to a world-class adaptive optics system.

The near-infrared multi-object spectrograph FMOS will be a unique instrument with a multiplex capability of 400 over the wide field of view of 30 arcmin, a wavelength coverage from 0.9 to 1.8 microns and a spectral resolution of 500 and 2000. For many years there will be no similar or equivalent instrument at any competing large telescope. The science anticipated, such as a Sloan-like study at a redshift between 1 and 2, is truly exciting. This project is also good example how an international collaboration can help to make an extremely ambitious instrument financially affordable and possible in a reasonable time frame. The collaboration between NAOJ, Kyoto University, the Anglo Australian Observatory and the universities of Durham and Oxford has proven to be very efficient and smooth.

Hyper Suprime-Cam will build on the outstanding scientific success of Suprime-Cam. With a much larger field of view of 1.5 degrees, an exquisite image quality over the whole field and very efficient CCD detectors it will become a revolutionary wide field deep imager able to address fundamental questions of astronomical science and also to prepare for the science with next generation Extremely Large Telescope. While this project requires a considerable effort including a modification of the telescope prime focus unit, it is certainly a key step to guarantee an important scientific future of an 8-m class telescope in the future era of 30-m class telescopes.

To use the same field of view as supported by Hyper Suprime-Cam for high and medium resolution multi-object spectroscopy with a multiplex capability of 4000, as suggested for WFMOS, would be next consequent bold step into the same direction. The committee understands that WFMOS is an expensive instrumentation project that will rely on solid financial and technical support from the Gemini community, which is yet to be committed. Nevertheless, a future constellation on Mauna Kea with the Thirty Meter Telescope (TMT), Subaru with Hyper Surprime-Cam and WFMOS and the University of Hawaii Pan-STARRS telescope is a vision of breathtaking scientific power.
The committee urges the Subaru Telescope to enter into a dialogue with the Japanese astronomy community about WFMOS.

The PIAA (Phase Induced Amplified Apodization) extreme adaptive optics system using the innovative concept of an apodized pupil without losing light and avoiding very strong off-axis aberrations has the clear potential to revolutionize astronomy in space and on the ground. It will make high dynamic range and high contrast coronographic observations possible on hitherto unprecedented spatial scales. This new technology might be the breakthrough towards the detailed astronomical studies of the physics of extra-solar planets and planetary systems. The development of the basic concept and the design and construction of the first system have all been carried out at Subaru, which provided the fruitful and supportive environment for such an initiative. Because of its obvious applications in space astronomy the project is now also supported by NASA and by awards from U.S. government. This is a spectacular success of research and development at Subaru. Together with the excellent results in the development of new instruments and more efficient detectors it indicates the success of the research and development carried out by Subaru researchers which is internationally competitive at the highest level.

The future plans for the Subaru Telescope are ambitious and bold. They keep the momentum obtained from the present success and envisage an exciting scientific future for Japanese astronomy. The committee is very supportive of these plans.

### 2.6 Self-Evaluation

The Review Committee has studied the self-evaluation material provided very carefully and has discussed every evaluation item in detail. The self-evaluation by the Subaru Telescope is comprehensive, thorough and fair. Since many aspects of the evaluation have already been discussed in the previous sections, only a brief summary is given here.

#### 2.6.1 Evaluation of Status of Research Activities, and User Support and Collaborative Research Activities

The list of outstanding achievements and papers is impressive. The committee agrees with the ranking as “SS” or “S” in each individual case. The rating “A” for the self-evaluated level of the results from the inter-university user support and collaborative activities is certainly justified. The reasons given for the common use, research output and instrument development are sound and convincing and the areas of outstanding achievements agree with the committee’s assessment.

The committee also agrees with rating “1” for quality improvement. The telescope, in particular, the image quality delivered is outstanding. The output is excellent, as is the development and operation of instruments. The transition to self sustained operation has been successful.

#### 2.6.2 Evaluation of Achievement of Middle-Term Objectives

The rating “A” on user support and collaborative research activities is certainly justified. The comparison of the Annual Plan with Status of Progress is impressive. The committee agrees with the analysis. Rating “B” on the graduate school education appears to be fair.

The statistics indicate a healthy program given the remoteness from other Japanese academic institutions. It is clear that Subaru has a positive impact on graduate education.

The rating “B” on public relation, community outreach, and international collaboration is fair. The statistics on outreach activities, press releases are impressive. The participation in the Imiloa Center is a thoughtful and successful development.

### 2.6.3 Future plans

The future plans are fully supported by the Review Committee. A detailed discussion has been given in section 2.5.

### 2.6.4 Others

The aspects of the ELT Project will be discussed in the next section.

## 3. Extremely Large Telescope

There have been remarkable developments over the review period in Japanese preparations for participation in an Extremely Large Telescope. In the early years of this period an extensive set of design studies was undertaken towards a 30m JELT based on the `baumkuchen’ primary mirror configuration. This work, led by Iye, established a strong basis for the scientific, technical and industrial participation of Japan in an ELT project. The scale and cost of constructing a 30m telescope led to the project’s decision in early 2007 to seek to join the California led Thirty Meter Telescope project should that telescope be sited on Mauna Kea. A major advantage of this approach is that Japanese astronomers will gain access to the first ELT to be built as, at present, TMT appears to be the most advanced ELT project. The committee views this decision very positively and urges the Japanese community to use the full weight of its considerable influence to ensure that the TMT ***is*** built on Mauna Kea. This is now a matter of the highest priority and greatest urgency. The presence of the Subaru telescope, and its headquarters in Hilo, will give the Japanese community both confidence in the success of the TMT and a head-start in exploiting it.

Potential for the involvement of Japanese industry in TMT is being rapidly elucidated. The requirement for over 600 1.4m blanks is an opportunity for Ohara using their *Clearceram* material. It seems likely that to achieve the necessary rate of delivery TMT will engage more than one mirror blank producer and Ohara are in a strong position. It will be a significant development if Japanese industry can provide some or all of the primary mirror segments. The light-weighted Zero Expansion Pore-Free ceramic (ZPF) has significant advantages but mass production and polishing need to be demonstrated in a way compatible with the TMT schedule. Canon could possibly demonstrate their polishing capabilities with existing facilities and would need to develop a new plant to deliver polished blanks at the required rate. The opportunity build on the success of Subaru in the areas of instruments, archives and operations offers the potential for Japan to contribute to TMT across almost all the important facets of the project.

The work of Prof. Iye in bringing the JELT design studies to fruition and in making strong connections with TMT has been remarkably successful. In the immediate future the ELT project office needs to engage the wider Japanese community to endorse participation in TMT as the highest priority following the completion of ALMA. The aspiration for Japanese astronomers to build two instruments for TMT will be an effective tool in engaging the community. Scientific workshops and technical studies are needed to make proposals for specific TMT instruments. These should get underway as soon as possible to identify this crucial contribution to the project. In parallel, by 2011 a comprehensive proposal needs to be developed to secure funding. The committee recognizes that work involved requires a substantial expansion of staff effort in the project office and strongly supports this development.

## 3.1 Self Evaluation

### 3.1.1 Research activities

**(a) Research outputs : self evaluation : 2 = commendable.**

The 2005 report on JELT and 2007 proposal to join TMT represent very significant steps forward. They are underpinned by high level technical studies over a range of activities and the self evaluation document mentions both ZPF mirrors and laser guide star adaptive optics each of which is a major advance worthy of the level assigned. The committee endorses the evaluation of the papers as `S’. Iye’s personal scientific contributions are exceptional and are certainly at the level of `1= distinguished’, they have been evaluated as part of the review of the Optical/IR Division.

**(b) Quality improvement: self evaluation : 1 = improving significantly.**

The committee endorses this evaluation. The move towards participation in TMT and the rapid embedding of potential Japanese contributions shows a very strongly improving position.

### 3.1.2 Mid-term plans : self evaluation : B = exceeds the level expected.

The committee judges that progress measured against the mid-term goals has been excellent and evaluates this as A = sustained exceptional level. The reasons for this are presented above.

### 3.1.3 Future plans

The future direction is now clear and laid out in these plans: establish the Japanese contributions to TMT, explore and select which instruments should be constructed in Japan, build community support, establish a formal partnership and prepare the budget request. Japan has already built strong links with the TMT international partners and we urge the expanded project team to continue these efforts. The principle goal for Japan in the TMT is *to secure access to the world’s first ELT* and therefore every effort should be made to sustain the rate of progress at the highest possible level.

**Roger Davies** **Rolf Kudritzki (Chair)** **Haruyuki Okuda**