

The Report of the ULTIMATE-Subaru review

March 31, 2016

The ULTIMATE-Subaru review committee

Executive Summary

ULTIMATE-Subaru (hereafter, referred to as ULTIMATE) is a next large instrumentation project of Subaru Telescope. The main part of the project consists of two instrumentation plans, a next generation adaptive optics (AO) system and wide field infrared instruments which utilize the unique capability of the new AO system.

The review committee thanks the ULTIMATE team for providing the well documented Study Report of the project for us. The presentations on key topics of the project and the questions and answers following them in the review meeting were very helpful for us to understand and evaluate the project.

The review committee found that ULTIMATE will enable Subaru Telescope to be a leading facility worldwide in the field of near infrared astronomy in 2020s – 2030s. The Ground Layer AO (GLAO) will be the key feature of this project. Wide variety of science cases will be able to be performed by ULTIMATE. In particular, wide field narrow-band surveys of distant galaxies will give a great impact on galaxy evolution studies. However, the consequence of the time delay with respect to competing facilities (about ten years from now to the completion of the project) should be seriously considered in planning science projects with ULTIMATE. Three different instruments are proposed by the team; the wide field imager, the multi-object spectrograph, and the integral field unit spectrograph. Among them, the imager is most attractive and should be realized first. The development plan and team organization are not mature in the current phase and deserve further consideration.

The detailed comments and recommendations on five review items of the ULTIMATE project based on the Study Report and the review meeting held on Feb. 24th 2016 are shown below.

(1) Science cases

Questions from the ULTIMATE team: *Are the science cases proposed by ULTIMATE team strong enough? We tried to assemble as wide variety of science cases as possible from Subaru community, but are there any science cases which are currently missing but which should be considered seriously? Similarly, considering the performance of ULTIMATE, please point out if there are any future projects or teams to be more closely collaborated with which strong synergy is expected.*

[Comments]

The science cases described in the study report are important and span many fields in astronomy, demonstrating the wide utility of ULTIMATE. The review committee congratulates the ULTIMATE team for

the broad range of science cases they have developed to guide the technical design of the overall Subaru upgrade plan. The core science cases concern the narrow-band surveys of very high redshift (via Lyman- α) and of “High Noon” $z \sim 2$ galaxies (via H α), the latter ones both in the field and in clusters. There is also the possibility of studying nearby star-forming galaxies using Pa- α , allowing the exploration of even highly obscured star-forming regions. These science cases are very strong.

[Recommendations]

The review committee recommends demonstrating more clearly that ULTIMATE can still lead the proposed science cases in ten years from now, and describing which science cases can be done only with ULTIMATE.

The first-light of ULTIMATE is assumed to be in mid 2020s, while there are or will soon be several competing instruments as shown in Table 7.1 of the Study Report. For example, capabilities to map the star formation rate surface density of distant galaxies at ~ 1 kpc resolution (via emission lines, UVJ, ALMA, or other means) is partly already in place or will become available well before the completion of the corresponding part of the ULTIMATE plan. The same considerations as for imaging science cases above apply also to the MOS and IFU science cases, some of which are still quite sketchy (especially the IFU ones). The IFU science cases do not appear to be built on the already existing scientific experience with AO-assisted IFUs. How can ULTIMATE still break new ground almost ten years from now? What requirements should this set on the design of the instrument?

The review committee acknowledge that it is not easy to look so deep into the future at a time when major new facilities are about to become operational. This is one more reason to ensure that with ULTIMATE will continue offering unique capabilities also in the near infrared.

In addition to the above fundamental recommendation, the committee recommends to the team to consider the following points in order to make the proposal even stronger and to gain the support of the community.

1. High-redshift galaxies are not uniformly distributed in redshift space, but come in narrow spikes at different redshift in different fields. By using available redshift catalogs, it should be explored how much the number of detectable galaxies can vary from field to field as a function of the central wavelength and passband width of the NB filters. This should also take into account the known distribution of the OH lines. What characteristics should the ULTIMATE Imager and its filters have in order to maximize its flexibility and the number of detectable galaxies?
2. One issue that could be further emphasized is mapping bulge formation and quenching from $z \sim 2.5$ to the present. Resolved H α maps for statistically significant samples of galaxies would show the transition from a centrally peaked H α emission to a depressed or absent H α emission in the central regions, i.e., the transition from centrally peaked star formation rate to its quenching, signaling the emergence of quenched bulges. This would offer a crucial test for the current paradigm of inside-out formation, growth and quenching of galaxies. However, will this issue be still open some ten years from now?

3. The complementarity between NB, intermediate- and broad-band filters offers the opportunity, via accurate photometric redshifts, of identifying the specific line (hence redshift) of each line emitter. This opportunity could be further explored and emphasized.
4. The Galactic/stellar science cases are still in a preliminary stage and should be expanded, perhaps involving a broader participation from the community.
5. The proposed spatial resolution of GLAO, 0.2'' FWHM, may not be essential for some science cases that make use of this high spatial resolution just to improve sensitivity. Clarify which science cases indeed need this high spatial resolution as physical resolution and which only require it in order to improve sensitivity. In particular, demonstrate that the key science case cannot be carried out without the GLAO resolution.
6. The key science case and some other cases require a large number of nights (of the order of 100 nights), thus having strong impacts on the open-use operation of Subaru. Those numbers and their impact should be justified based on the minimum requested sample properties (e.g., sizes and depths) from the scientific point of view.

(2) Adaptive Optics (AO)

Questions from the ULTIMATE team: *At the beginning of ULTIMATE WG (2011-2012), we had an extensive discussion with Subaru community, and decided Ground Layer AO (GLAO) to be the best option as the Subaru Next-generation AO system. We believe that this is also well matched to the future direction of Subaru Telescope itself (i.e. wide-field, survey oriented telescope). Do you agree that the currently expected AO performance, i.e., ~0.2'' PSF size over ~15' FoV - sounds appealing enough for the community? Please let us know if you have better ideas or suggestions on AO performance which can potentially enhance the powerfulness of Subaru in 2020s.*

[Comments]

Overall, the review committee concurs with the opinion that if Subaru wants to remain a competitive telescope in the near-infrared during the era of the extremely large telescopes (2025-2035), a wide-field AO capability is absolutely essential. In particular, choosing a wide-field solution supports optimally the Subaru strategy of remaining the world-wide best telescope for wide-field optical-infrared studies from the ground. Furthermore, the increased spatial resolution through AO will allow Subaru to approach the spatial resolution of space telescopes (JWST, WFIRST, EUCLID), and at the same time will enable observations at fainter magnitudes otherwise not achievable – which, in turn, will allow supporting work on the extremely large telescopes such as the Thirty-Meter Telescope (TMT).

The review committee thanks the ULTIMATE study team for their comprehensive and excellent report on

AO. Chapter 6 of the report outlines performance modeling for various types of AO, presents first technical solutions for a GLAO system, and provides a preliminary analysis of the implementation of GLAO on the Subaru telescope.

The trade-off study between GLAO, Multi-Object AO (MOAO), Laser Tomography AO (LTAO) and Multi-Conjugated AO (MCAO) is well documented. The thorough simulations of GLAO appear realistic when compared to similar simulations for the VLT/GRAAL system, providing credibility to the expected performance. The review committee agrees with the finding that tomographic AO (multiple guide stars) should be pursued at Subaru, and that, among the options, GLAO is the best solution to match Subaru's scientific goals.

The system modeling presented in chapter 6.2 is well researched. The review committee supports the ULTIMATE team's approach to build on existing technology for the Adaptive Secondary Mirror (ASM). The considered solution is based on experience at ESO (Very Large Telescope) and the Large Binocular Telescope and minimizes research and development efforts as well as technological risks. The team has clearly researched some of the problems with existing ASMs and presented good mitigation strategies. Similarly, the solution for the four laser guide stars relies on infrastructure that will exist by then (using the already planned new TOPTICA laser, splitting it into two beams, and adding a symmetric laser to provide all four natural guide stars). Finally, good ideas have been presented for the Wave-Front Sensor (WFS) solution as well with various solutions for low-noise detectors and first studies of Shack-Hartmann WFSs. The review committee strongly supports the overall low-risk solution that will enable to keep the development of the full GLAO system on a reasonable budget and controllable schedule.

Finally, the ULTIMATE team has identified the necessary telescope modifications needed to fully exploit the maximum FoV for GLAO: the Cassegrain flange, including the telescope incorporated telescope functions, will need to be replaced to accommodate the WFS units and allow for an expanded 15 arcminute FoV.

[Recommendations]

On the technical side, we recommend investigating further the Rayleigh laser solutions, which could represent significant cost savings (~\$1M?). We also recommend continuing GLAO experiments with RAVEN, if feasible, in order to further characterize the turbulence profiles above Maunakea and to validate the expected GLAO performance. Furthermore, we strongly recommend that the ULTIMATE team contacts the ASM teams at the VLT and MMT telescopes (in addition to the LBT ASM team) in order to maximally profit from the lessons learned by these other team, and to fully exploit the advantages of using existing technologies.

On the scientific side, the review committee recommends discussing further the science plans for 'above average' seeing conditions. One challenge unique to Subaru will be the co-existence of an ASM together with prime focus instruments (HSC and PFS). This implies regular on/off swaps of the ASM and means that GLAO will have to be used during all the bright time in a given month. It would be wise to develop science plans for the nights in which the seeing will be worse than average and the GLAO performance modest. Further, we recommend keeping an eye on the competitors in the 8m-class telescopes with GLAO: at the

VLT, HAWK-I with GRAAL will have a head start of almost ten years – the ULTIMATE team should carefully consider in which areas it wants to compete and where it wants to complement these capabilities. Similarly, the development of instruments at the LBT should be monitored.

On the project side, the review committee recommends looking into a two-phase implementation of the ULTIMATE facility on Subaru. In a first phase, the GLAO system could be developed and potentially be used with already existing instruments (in the Subaru suite of instruments, or perhaps even considering loans from other observatories – we recommend conducting a comprehensive study). Such an option would offer the opportunity of starting to exploit the GLAO facility while new instruments may still be under construction.

Finally, the project, including the GLAO system, needs to conduct more work in order to produce a full work breakdown structure, which is required to develop a realistic budget and schedule for the project.

(3) Instruments on ULTIMATE

Questions from the ULTIMATE team: *In the study report, we mention three possible instruments on ULTIMATE (i.e. wide-field imager, MOS spectrograph, multi-IFU instrument), according to the science requirements. It is of course true that we want to have everything, but considering the manpower and budget situation, we might need to prioritize these instruments. Which instrument do you think is the most important (or the most compelling instrument in 2020s)? This point will be closely related to your comments on science cases, but here we hope you to take into account the possible impacts on the instrumentation community in Japan as well.*

[Comments]

The review committee thanks intensive efforts for instrument design studies by the ULTIMATE team with international collaborators. All three instruments would be attractive and unique, if they were in operation just right now. But if we consider that ULTIMATE will only be available in ten years, a unique and/or superb capability is desirable. Basically, all the instrumentation should be driven by strong science cases, but it is important to keep in mind that a unique instrument may open windows for new scientific topics.

(a) The wide-field imager

The wide-field imager is a natural option as the first instrument combined with the GLAO secondary. A GLAO-assisted imaging mode over a field as wide as 15 arcminutes appears to ensure a unique capability for Subaru.

The current design is, however, too heavy to be installed at the Cassegrain focus. In addition to the technical feasibility, the ULTIMATE team should further look for good ideas to make the instrument unique and cost effective, combined with pre-studies for science. For example, in the case of galaxy evolution

studies, it looks that of order of several dozens of NB filters would be required, with a cost of ~100 K\$ each they could add a few M\$ to the cost of ULTIMATE. A more precise estimate of the number of NB filters needed by the various science cases (different fields, redshifts, clusters of galaxies, etc.) would have been appreciated.

Changing filter sets is correctly mentioned as an opportunity only ground based telescopes can offer. But this may come at the cost of submitting the instrument to frequent thermal cycles, which represent a nontrivial operational burden and can compromise the health and longevity of instruments.

(b) The multi-object spectrograph

The multi-object spectrograph combined with the GLAO system has advantages because of high spatial resolution. Compared with PFS, the spectrograph will be complementary with NIR wavelength coverage. But the current optical designs are still in a very preliminary stage; none of the current designs can cover the 15 arcminutes FoV due to technical difficulties. A multi-object spectrograph with limited FoV may be acceptable and realistic, if superior capability compared to existing instruments is significantly achieved. For example, it could be studied whether MOIRCS could be used as a first instrument, with minimal modifications. Even in this case, the weight limit of the Subaru Cassegrain focus (2.5 tons) should be carefully addressed.

(c) The integral field unit (IFU)

Deployable IFUs is a feasible option to cover the 15 arcminutes FoV. MOIRCS can be used as the first spectrograph, followed by a dedicated spectrograph with more detector pixels. However, the current design is still quite preliminary. Compared to existing near-IR IFUs, it would lose the K band because no single fiber can achieve good throughput from 0.9 μ m to 2.5 μ m. It also would lose gain in multiplex and possibly image quality. In addition, the competitiveness after a ten year delay should be carefully considered.

[Recommendations]

Overall, designing a wide-field NIR instrument for 8-m class telescopes that will profit from a GLAO corrected 15' field of view is very challenging, and the review committee recommends carrying out further design studies, possibly involving other Subaru instrument developers once they complete projects in which they are currently occupied.

The review committee is explicitly asked to suggest how to prioritize the three instruments. Having said that the three GLAO-corrected instruments, with their wide FoV, would offer capabilities unmatched at other telescopes. As far as a new instrument is concerned, it is the impression of the review committee that at this stage **the wide-field imager should be seen as the first instrument** for the new ASM configuration of Subaru. Then followed by the MOS and the IFU (which appears in a more preliminary stage of design). The science cases for the NB and IB filters also appear more clearly elaborated than those for the other two instruments. However, recycling MOIRCS as part of the GLAO upgrade may offer an attractive option for spectroscopy, at least for the early stages of ULTIMATE.

The review committee also recommends conducting a feasibility study of a cryogenic tunable filter for NB

imaging capability. The tunable filter would offer several technical and scientific advantages. It will eliminate the need to change filters and will allow to tune the filter to specific redshift spikes (either in fields or of clusters). It would thus offer maximum versatility and efficiency in recovering line-emitting galaxies, and would be very attractive also for Galactic studies and those of nearby galaxies. An infrared tunable filter over a 15 arcminutes FoV on a GLAO-assisted imager would be a unique facility worldwide.

(4) Development plan & Team organization

Questions from the ULTIMATE team: *Is the development plan (first light in 2023-2024) that we are proposing feasible enough? Please point out if there are any critical points that are currently missing. ULTIMATE is not funded yet, and accordingly the manpower is very limited at this moment. We recognize that the development plan is still premature at this stage, but please provide us your comments on which parts of the project we should take care more closely. Your comments based on your experiences with big projects are highly appreciated.*

[Comments]

Compared with the prime focus, the Cassegrain focus of the Subaru telescope is not particularly unique among 8-m class telescopes. On the other hand, the estimated cost to build a wide-field instrument and to upgrade the Cassegrain focus is significant, and it may be difficult to get the whole ULTIMATE funded at once. The development plan is still premature as noted, and significant amount of efforts are required to break down the tasks and to carry out the cost and human resource analysis. Delivering the GLAO system and 3 instruments by 2023 appears too challenging. The structure of the project team seems to be complex, and should be simplified with a strong PI and a well experienced instrument leader. The Subaru AO team used to be powerful, but many members have moved to Mitaka. Inviting new staff to the Subaru observatory is important.

[Recommendations]

As described in the AO section, the review committee recommends considering a two-phase development plan; developing the GLAO for existing instruments with minimum telescope upgrades first, then developing wide-field instruments with necessary telescope upgrades for 15 arcminutes FoV. During the first phase, the team can consider intensive R&D for some components of the instruments, and/or can study new ideas for a breakthrough. The two-phase strategy would also be beneficial to early start on ULTIMATE science. The Subaru users will be able to start their science projects with the GLAO immediately after its completion. And the feedback from these science activities would help improving the designs of the new instruments in the second phase.

The review committee recommends identifying a strong PI who conducts the whole project with responsibility, and recommends constructing the project team with a simple straightforward structure. The

committee also recommends the ULTIMATE team to contact instrumentation experts in VLT, Keck, Gemini, or other facilities. Inviting other groups into the ULTIMATE team would be important not only for instrumentation but also for science, as scientific input to the instrumentation design is still essential.

(5) Final question

Questions from the ULTIMATE team: *Do you agree that the ULTIMATE is ideally suited and best matched strategically to the direction of Subaru Telescope future? We hope to have your constructive suggestions and comments to realize ULTIMATE from various aspects.*

The Subaru Telescope has established itself as a leading facility worldwide by offering a unique set of capabilities. ULTIMATE goes on with this excellent tradition, with the wide field GLAO facility and its set of science instruments. This appears to be the wisest long-term strategy for Subaru, better than trying to duplicate capabilities already existing or planned at other telescopes. What is really critical for ULTIMATE, is that its capabilities should make Subaru a UNIQUE facility also in the near infrared, offering flexible observation modes unparalleled at other telescopes.

If Subaru wants to remain a competitive telescope in the near-infrared during the era of the extremely large telescopes, a wide-field AO capability is absolutely essential. The review committee agrees with the ULTIMATE team that GLAO is the best solution. The wide field imager is the most suitable for the “first light” of ULTIMATE among the three types of instruments proposed in the Study Report. The review committee also understands the importance of a wide field multi-object spectroscopy capability for various science cases. We thus recommend the ULTIMATE team to consider utilizing existing instruments like MOIRCS as a first multi-object spectrograph of ULTIMATE after completion of the wide field imager, or to look for a possibility to integrate spectroscopy function to the imager.

The current ULTIMATE proposal is very big and the estimated cost, about US\$ 50 million, may be too high to be accepted by funding agencies as a whole. The two-phase implementation plan suggested several times in this review would be one solution to the funding issue. The two-phase strategy would also make it possible to start some ULTIMATE science with existing instruments such as MOIRCS in the early 2020s. The whole GLAO system (ASM, WFS, and lasers) is based on already mature technology and may require a relatively limited Subaru manpower. The review committee recommends considering modification of the whole development timeline by shortening the timeline for GLAO and have MOIRCS (still in MOS mode) as the first light instrument with GLAO.

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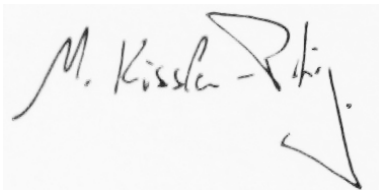
Michitoshi Yoshida (chair)



Mamoru Doi



Markus Kissler-Patig



Kazuhiro Shimasaku



Alvio Renzini

