CATAC recommendations for the Wide Field Optical Spectrograph on TMT

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Executive Summary

CATAC has considered the three conceptual designs proposed for WFOS and reached the following conclusions:

- **Fiber-WFOS** is an ambitious, exciting design that recovers the large field of view (FOV) originally envisioned for the instrument, with a high multiplex capability using modular, fiber-fed spectrographs. The FOV in fact exceeds the current top level design requirements. The design further exceeds requirements by enabling simultaneous wavelength coverage over 310-1000nm and including an IFU capability. It fails to meet the top level requirements to provide imaging and a range of spectral resolutions.
- **Slicer-WFOS** is an innovative, monolithic design that uses a traditional slit-mask for R=1500, but achieves R=5000 using image slicers. Like fiber-WFOS, it exceeds design requirements by providing simultaneous wavelength coverage over the full range, and fails to meet the imaging requirement. While it does provide two resolutions, this does not adequately satisfy the requirement for a range of resolutions.
- **Xchange-WFOS** is monolithic slit spectrograph, that uses VPH gratings and articulated cameras to satisfy the top level requirement of providing a range of resolutions. It includes an imaging capability, and also meets the requirements for wavelength coverage. Like slicer-WFOS, it provides a FOV of 25 square arcminutes, which does not formally meet the top level requirement (>40.5 square arcminutes); this has, however, been the effective target FOV since the MOBIE design.

We conclude that Xchange-WFOS is the design that best meets the top-level requirements, without exceeding any of them. In addition, it is the most versatile and flexible of the three designs, best matching the workhorse capability that is considered most valuable at first light to most in the Canadian community.

Fiber-WFOS is well suited for large, survey-type science that we expect to become more important as TMT matures. It would make an excellent candidate for a later generation instrument.

Background

The Wide Field Optical Spectrograph (WFOS) represents a unique and critically important capability for the Thirty Meter Telescope (TMT). The European Extremely Large Telescope (ELT) will not have an optical multi-object spectrograph (MOS) at first light, so there is an opportunity for TMT to have a huge impact here despite the delays the project is facing. Multi-object spectroscopy in general is an important capability for Canadians, who broke much of the ground in this area with CFHT (e.g., the CFRS and CNOC surveys), and for whom GMOS remains the most subscribed instrument on Gemini. For these reasons, CATAC is paying close attention to the development of WFOS, in light of how it aligns with Canadian scientific interests.

We start by recalling some of the top-level requirements for WFOS as they stand today. We restrict the list to those requirements that have discriminated between various designs, past and present.

> **[REQ-1-ORD-3905]** WFOS shall be able to take an image of its spectrometric mode field of view.
> **[REQ-1-ORD-3950]** WFOS shall have a wavelength range of 0.31 - 1.0μm; 0.3 - 1.5μm (goal).
> **[REQ-1-ORD-3965]** The WFOS field of view shall be > 40.5 square arcmin.
> **[REQ-1-ORD-3970]** The WFOS total slit length shall be ≥ 500 arcsec.
> **[REQ-1-ORD-3980]** WFOS shall have a spectral resolution of R = 500-5000 for a 0.75 arcsec slit.
> **[REQ-1-ORD-3985]** WFOS, in Spectroscopy Mode, shall have a throughput of ≥ 30% from 0.31 - 1.0μm, not including the telescope.
> **[REQ-1-ORD-3990]** WFOS spectra shall be photon noise limited for all exposure times > 60 sec.
> **[REQ-1-ORD-3992]** WFOS background subtraction systematics shall be negligible (TBD) compared to photon noise for total exposure times as long as 100 Ksec.
> **[REQ-1-ORD-3997]** WFOS shall support short (< 3 minutes once telescope is in position) field acquisition for multi-slit masks.
> **[REQ-1-ORD-3999]** WFOS shall support fast (< 1 min) acquisition of single targets onto a long slit.

We also recall a couple of Observatory requirements relevant for target acquisition:

> **[REQ-1-ORD-1805]** The TMT Observatory shall perform the complete target acquisition sequence in less than 5 minutes when an instrument change is not needed.
> **[REQ-1-ORD-1810]** The TMT Observatory shall be able to change from one instrument to another instrument already installed on the telescope in less than 10 minutes, starting from the end of an observation in one instrument to the start of observation in the other.

WFOS has proven challenging to design to specifications. The original top-level requirement was for an instrument with a field of view of >75 square arcminutes. The first design, HIA-WFOS, was a four-barrel spectrograph that used slitmasks and covered a >100 square arcminute field. Six interchangeable gratings per camera would be used to provide flexible resolution settings between 500 and 5000. In early 2007, the top-level requirement on field of view was changed to 40 square arcminutes as the HIA-WFOS design was descoped down to a two-barrel design driven by the need to contain cost.

In late 2007, the WFOS design was fundamentally changed in a move to re-capture some of the high-resolution science that was lost when it was decided that a high-resolution spectrometer would not be available at first light. The "Multi-Object Broadband Imaging Echellette" (MOBIE) spectrometer featured a R=8000 cross-dispersed mode that formally exceeded top-level requirements. In particular, the SAC was attracted by the possibility of obtaining higher resolution spectroscopy with full wavelength coverage. However, an increase in instrument cost in 2011 led to another change in the field of view down to 25 square arcminutes; this change was never formalized in the top-level requirements.

Both early designs were imaging spectrographs, as required [REQ-ORD-3905]. Both offered simultaneous wide wavelength coverage (a design goal), multiple resolutions [REQ-1-ORD-3980], and emphasized the need to reach Poisson-limited noise [REQ-1-ORD-3990, REQ-1-ORD-3992].

A review in May 2017 concluded that the MOBIE design was too risky to pursue. This led to the current three designs developed by the instrument team under the leadership of Kevin Bundy. They are summarized in the Table below. Given the importance of WFOS to the Canadian community as a first light instrument, and the existence of three compelling but very different instrument designs, CATAC considered it critical to gain an understanding of which design would best serve the Canadian community so it could provide Canadian SAC and Board members with informed advice.

	Multiplexing	**FOV (sq arcmin)**	**Resolution**	**Peak throughput**	**Wavelength coverage (nm)**	**Imaging Mode**
Fiber	468	79	Fixed (default 5000)	57%	310-1000	No
Slicer	70/23	25	1500/5000	67%	310-1000	No
Xchange	91	25	1500, 3500, 5000, possibly up to 15000	67%	310-1000 at R=1500; 5 settings at R=5000	Yes

Methodology and Consultation

The following consultations were made:

- CATAC received a thorough presentation by the instrument Principal Investigator Kevin Bundy about the capabilities of the fiber-WFOS and slicer-WFOS designs, on Dec 19, 2017.
- CATAC read and reviewed the original Operational Concepts Definition Document (OCDD) for the HIA WFOS design (Sept 23, 2005) and for the subsequent MOBIE design (v1.7, Dec 5, 2008). These were considered together with the TMT Observatory Requirements Document (May 9, 2017).
- CATAC next revisited the TMT Detailed Science Case 2015 (DSC). As points of comparison we also reviewed the Science Case for MOS on the European ELT (Jan 2015), as well as the capabilities of highly multiplexed spectrographs on 8-m class telescopes (Prime Focus Spectrograph on Subaru, and the proposed Maunakea Spectroscopic Explorer). We constructed an approximate mapping of science requirements to instrument capabilities.
- Based on the above, CATAC released a preliminary report to the community on Feb 13, 2018. This report highlighted areas where more detailed information was required. It also recommended that it would be useful to use some of the key science drivers to develop quantitative specifications that could be used to distinguish between the designs. This draft report was circulated to the community via the CASCA email exploder, and some email feedback was received.
- Following this report, we were provided with additional documentation in the form of the WFOS Optomechanical Design Review (OMDR, April 19, 2017) and some matrices mapping science to requirements, prepared by the project office.
- The Xchange design was introduced to CATAC after our February report was released. Some documentation was made available to CATAC, including the full WFOS Conceptual Design Phase 1 (CoDP1) document that presented details of three designs.
- CATAC prepared a brief summary of the three designs and distributed the information to the CASCA community via the CASCA email exploder on March 22, and invited participation at an open Webex meeting on March 27 for an open discussion of WFOS.
- During the March 27 meeting, opinions were heard from several informed members of the Canadian community. Several email contributions were received in the days that followed; some of these were solicited by CATAC, from people interested in science that was not well represented during earlier consultations.

In general, the MOBIE requirements (section 2.3 in the OCDD) were not demonstrated to flow directly from the top-level requirements of the telescope. In particular, they included requirements that were either stated as goals (simultaneous wavelength coverage, integral field unit [IFU] and GLAO capability) or were not included at all (e.g., R=8000 resolution). While it is reasonable to expect top-level requirements to change over the extended development time of a big project like this, it is also important that the top-level requirements drive the instrument design, as described well in Simard & Crampton (2010). CATAC has chosen to take this approach in making its recommendations.

Findings

Science Drivers

- A clear mapping between science and capabilities is required. The TMT DSC does not, in general, contain enough detail to critically distinguish between the three designs. In particular, the lack of source-density estimates and number of objects required to obtain sufficient statistics for the science goals were missing in many cases. This directly informs the field-of-view and multiplexing requirements that are relevant to the current downselect.
    - Several International Science Definition Teams have developed detailed matrices mapping science cases in the DSC to instrument capabilities. It is not clear how or if this information flowed down to the quantitative assessment of several science drivers that was written by a small team as part of the OMDR in May 2017.
    - Based on the available information, none of the three designs clearly stands out as superior in terms of its ability to carry out the science in the DSC.
- Transient science is recognized as an important research area, and will only be more so by the time WFOS sees first light. Rapid target acquisition (<5mins for close-to-open shutter on a new target with the same instrument, and <10 mins with an instrument change) has been a key top-level requirement [REQ-1-ORD-1805 and REQ-1-ORD-1810] for TMT from the beginning. It has had a major impact on everything in the TMT observatory design, and will be a unique TMT advantage. WFOS can and should play a role here, but the following points need to be considered:
    - The WFOS field of view is not generally useful for transient science. For follow-up work where one wants full wavelength coverage and high spectral resolution, the wide field and multiplex capability is generally not needed. On the other hand, the field is likely not wide enough to play a large role in finding gravitational wave and neutrino counterparts, where several square degrees of sky need to be searched.
    - 8-m class telescopes have and will have instruments specifically designed for transient follow-up (e.g., OCTOCAM on Gemini). This will likely go a long way to defining the most interesting types of transients for follow-up by the time TMT sees first light.
    - Simultaneous coverage of the full wavelength range at R=5000 is important for some transient science, like uncovering the physics of Gamma Ray Bursts. On the other hand, for supernovae, the lines are broad so R=1500 is generally

    sufficient. For host galaxy identification of gravitational wave detections speed is not essential, and simultaneous wavelength coverage is not critical.

- For extragalactic astronomy, the widest field spectrographs with good red sensitivity (e.g., VIMOS and DEIMOS) have dominated, historically. In most cases this is due to their ability to amass large samples (i.e., multiplexing), rather than area covered per se.
- Several members of the community noted that fiber WFOS would be best suited to their science, if it performs to specifications.
    - An important advantage of fiber-WFOS highlighted by some is the multiplexing advantage which allows certain programs (e.g., IGM tomography) to be carried out more quickly.
    - Many of the science cases in the DSC also benefit strongly from an integral field unit (IFU) capability, e.g., for resolved galaxy studies, and several members of the community also noted this as important for their science, particularly when coupled with ground layer adaptive optics (GLAO).
- Blue sensitivity is critical for some important science of interest to Canadians (e.g., white dwarfs, radial velocity studies of compact object binaries in star clusters). This requires coverage from 360nm to at least 720nm. Resolutions of 2000-5000 are needed, with the blue sensitivity generally more important than resolution.

General Design Considerations

- A core strength of WFOS on TMT is very deep spectroscopy with little to no systematics. An excellent blue response down to the atmospheric cutoff would be a unique capability among planned facilities.
    - If good throughput down to the atmospheric cutoff (310 nm) is required, this will drive many aspects of the telescope design; in fact the current mirror coating is optimized for the 0.3-14 micron range because of the Level 1 requirements. As there will not be a mid-infrared instrument at first light, further optimization in the blue may be possible. In that case all components must optimize for blue response, and that should include WFOS.
    - If TMT moves to ORM, near-UV sensitivity will be moderately reduced (by 20% at 350nm) because of the atmospheric cutoff at that site. The effect is not large enough to have a significant impact on the design choice.
    - The advantage of a large aperture telescope for spectroscopy is its ability to go deep. Compromise on throughput should not be accepted lightly.
- The wide field capability of TMT remains a discriminator with the ELT and should be exploited where possible. ELT-MOSAIC will have a 40 square arcminute field of view, however, so WFOS would have to significantly exceed design requirements to differentiate itself here.   We note that GMT has a maximum field of view of 20 arcminutes, like TMT, and the plate scale of GMT makes it easier to build wide-field instruments.
- Imaging is a top-level requirement [REQ-ORD-3905]; however it is reasonable to ask whether or not this requirement is still valid.

    - CATAC learned of no compelling science cases requiring WFOS imaging.
    - In the absence of a science case, the imaging capabilities for WFOS should be driven by operational issues and/or requirements for telescope/instrument commissioning. For example, target acquisition of faint objects will require high enough S/N to place the target in the Gaia reference frame. This can be done with moderately long (~1 hour) exposures on 8-m class telescopes; such access may not be readily available to all TMT partners.
- IFU capability features heavily in the DSC, but is not a design requirement. More information is needed on how, or if, this could be achieved with slicer-WFOS or Xchange.
- GLAO considerations should not be a critical aspect of the choice. The improvement expected from a future GLAO system is not likely to be large enough to drive this decision.
- Simultaneous wavelength coverage at R=5000 primarily serves some transient follow-up work. In general it is not required for diagnostic stellar spectroscopy, which has been shown to be successful with instruments like GIRAFFE on VLT, without simultaneous coverage. Nor is it critical for supernovae follow-up (where R=1500 is fine) or host galaxy identification of gravitational wave events (where using multiple grating settings is acceptable).

Specific Design Trades

- Most existing fiber spectrographs on 4m and 8m class telescopes have not generally been successful. In the past there have been promises that improved technology was going to revolutionize fiber spectroscopy, and those promises were not realized. There is a heavy burden of proof on the instrument team to prove that the throughput and sky subtraction with fibers can reach design specifications.
    - Despite this history, fiber performance clearly *has* improved, as demonstrated by the analysis the instrument team has done with MaNGA data. This and other work is demonstrating that in the near future fibers will likely to be able to achieve excellent sky subtraction, quite possibly reaching the TMT top level requirements. Especially at >800nm, however, this requires local sky subtraction, for example by pairing every science fiber with a sky fiber. There is a corresponding reduction in multiplex ability, though the number of science targets per field of view in fiber-WFOS will still exceed the other two designs by more than factor of two. To reach design requirements of 0.1% or better will require further improvements, and it is not yet clear where they will come from.
    - Although significant advances in fiber throughput have been made, fibers are unlikely to be able to mach the throughput of slit spectrographs, especially at the shortest relevant wavelengths. Figure 4 in the CoDP1 shows that Xchange at R=5000 is predicted to reach throughputs 70-80% in the red (850-950nm) with anticipated advances in VPH gratings. Fiber performance over the same range is

predicted to be ~45-57% (Figure 8 in the CoDP1). The difference is similar at the shortest wavelengths, and indeed over most of the wavelength range.

    - With typical 0.75” seeing, there is a small gain in throughput with the 7 fibre bundle relative to a slit spectrograph, as significant flux falls outside the slit. However this is not enough to compensate for the throughput difference at <450nm. Moreover, when the seeing is better than 0.75” slit losses are small and the fiber enjoys no such advantage in throughput.
  - The GHOST spectrograph, being designed and built in Victoria, will be the most sensitive optical spectrograph ever built (for a 8m observatory) when it gets delivered to Gemini later this year. GHOST is using the exact "fiber-slicing" idea of the fiber-WFOS concept (i.e., miniature IFUs that are reformatted into a slit to get higher resolution).
- Rapid acquisition may be better done with the proposed fiber design (i.e., with a 37-fiber bundle fixed at the field centre) than with slits. However, all three designs are expected to be able to meet the top level specifications for acquisition without difficulty.
- R=5000 may not be the optimal resolution for the high-resolution mode, especially if multiple resolutions are available. We heard that $R \gtrsim 6000$ would be a better choice for line diagnostic work; DEIMOS has been a huge success working at this resolution. New opportunities only open up significantly after that for R=20,000, which could be achieved by WFOS using a 0.25” slit, or slicers. As this goes beyond top-level specifications, however, the benefits have to be carefully quantified and weighed against additional cost.
- The CoDP1 concluded that slicer-WFOS is not a compelling choice because:
  - The need for multiple slicer designs adds complexity
  - It is difficult to meet requirements on telecentricity
  - Plugging operations are tedious, with “significant effort required to ensure that a robotic solution was viable”.
  - There are concerns about potential problems with stability resulting from flexing of the modules at the focal plane.

  The documents provided to CATAC do not contain enough information to understand the severity of these issues. However, as presented, the first three do not appear to be “show-stoppers”. The final concern, about stability, is potentially worrying; however without quantitative detail we cannot comment further on how fatal this is to the design.

Operations

- Fiber-WFOS is most naturally suited to survey science: large programs that require covering large areas of sky, usually supporting multiple science goals. CATAC did hear support for this mode of observing. Other members in the community are more excited about using TMT for typically shorter and more targeted programs, where they can find new and creative ways to use the instrumentation to address science in 2030 that it is impossible to predict now. An instrument like Xchange-WFOS is better suited for this.

- With queue mode operations, compelling science programs can request exquisite seeing conditions that are frequently available, especially on Maunakea. Both the fiber and Xchange designs can benefit from this. The fiber-WFOS 7-fiber bundle acts as a mini-IFU and source flux can be optimally extracted by mapping the PSF across the field. Xchange (or slicer in its low resolution mode) can similarly increase sensitivity by using a narrower slit, which has the added benefit of simultaneously increasing spectral resolution without corresponding throughput losses.

Conclusions

- All three designs are compelling and will enable excellent science to be done.
- If fiber-WFOS is able to achieve the top-level design specifications, it will be a highly capable instrument that takes advantage of TMT's wide field of view. The burden of proof to demonstrate that fiber-WFOS can meet specifications in throughput and sky subtraction is very high.
- The lack of flexibility to choose resolution with fiber-WFOS is a serious concern and represents a compromise for many in the community. The throughput disadvantage relative to a slit spectrograph, over much of the wavelength range, compromises one of the most critical advantages of a large telescope. As an instrument most naturally suited to survey science, it may be better suited to a later generation rather than a first light instrument.
- Good sky subtraction at long wavelengths with fibers will likely require reducing multiplex capability by a factor of two. This reduces the multiplex advantage relative to Xchange-WFOS. Xchange will in that case provide a higher maximum target density, of ~3.5 per square arcminute, compared with ~3 per square arcminute for fiber-WFOS.
- The top level requirement that WFOS be able to take an image of its field is considered an important component of a flexible, workhorse instrument. Though a specific science driver for this capability does not seem to have been identified, it is hard to predict what will be important in 2030. If a workhorse capability is desired, then a decision to abandon this requirement should not be taken lightly.
    - Moreover, the consequences of a lack of imaging, beyond direct science applications, need to be considered. In particular, sufficiently deep imaging may not be available to all the TMT partners from other telescopes to enable target selection and acquisition. While a combination of LSST and Pan-STARRS imaging would be sufficient for most applications, these data are not expected to be made publicly available to all partners. This limitation is particularly relevant for transient follow-up, since such events could occur in poorly imaged areas of sky.
- There are scientific benefits to pushing the highest resolution modestly beyond the requirements of R=5000, to at least R=6000. For an instrument like Xchange where a lower resolution option is available, this bears consideration.

    - Adding slicer modules to Xchange would then enable R=20,000, where fundamentally new science opportunities present themselves. This would provide a HROS-like capability at first light. Even a single slicer placed at the centre of the mask would be useful. Without slicers R=20,000 could still be achieved with narrow slits, at the cost of throughput. This option further increases the flexibility of the design.
- Based on the information available, CATAC was surprised at the conclusion of the CoDP1, that slicer-WFOS is a significantly more complex or risky design than Xchange. Opto-mechanically, slicer WFOS is the low resolution mode of Xchange-WFOS, but without any moving parts. This greatly simplifies things, decreases the rotating structure mass and simplifies flexure control. It is not clear why the robotic plugging of slicer modules is considered problematic.
    - However, slicer-WFOS does not meet top-level specifications, because it does not have an imaging capability. More importantly, it has only two resolution settings. While this formally satisfies the requirement for multiple resolutions, it does not satisfy the spirit of the specifications, which we interpret as defining a workhorse, flexible instrument able to satisfy a broad range of science cases proposed by a diverse international community.

Recommendations

- The advantages of Xchange-WFOS - namely the flexibility in resolution and slit size, and the throughput at most wavelengths - weigh heavily against the disadvantage in multiplexing relative to fiber-WFOS, especially when 50% of the fibers are used for sky. Xchange-WFOS is a familiar design with significant heritage; therefore the risk of not performing to specifications is considered to be low. Indications are also that this design is likely to be cheaper than fiber-WFOS. For these and other reasons, the Xchange-WFOS design is the one we recommend most strongly.
- Slicer-WFOS offers the advantage of simultaneous, full-wavelength coverage at R=5000; this was highlighted as important for follow-up of some transient events. Simultaneous coverage is beyond the top-level requirements, however, and it is not appropriate for the needs of a few important, but specific, science cases to overly constrain the design of a general purpose, wide-field instrument like WFOS. Slicer-WFOS also fails to meet requirements as it lacks imaging capability and offers only two resolution modes; it also has the smallest multiplex capability of the three designs. Therefore, CATAC does not recommend proceeding with this design.
- Fiber-WFOS is a highly-capable instrument that CATAC would be excited to see as a next generation capability. Given the strategic importance of WFOS, and the associated risks and costs of fiber-WFOS, CATAC believes it is important to wait to evaluate the performance of spectrographs like GHOST and PFS before committing to this route.

- For Xchange-WFOS or slicer-WFOS, CATAC recommends the SAC consider the cost/risk implications of increasing the highest resolution mode (without slicers) to at least R=6000.

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