Submillimetre Galaxies and Extremely Red Objects: Expectations for FMOS in the Light of OHS Observations

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ABSTRACT

FMOS promises to provide near-infrared spectroscopy of a quality far superior to that of any existing instrument. In this paper I attempt to extrapolate from existing OHS observations to predict what FMOS will see when it observes two important classes of source for which it appears well-suited, namely submillimetre galaxies and extremely red objects.

1. INTRODUCTION

As this workshop plainly revealed, FMOS promises to be an exciting and innovative new instrument which will revolutionize near-infrared spectroscopy. For those of us who have been battling at the limits of OHS's sensitivity, the prospect of obtaining much higher quality spectra of as many as a thousand objects in a single night is one to relish. In this paper, I examine the data quality expected from FMOS observations of submillimetre galaxies and extremely red objects, two classes of source for which FMOS seems ideally suited. To do this, I use data which my collaborators and I have obtained using Subaru Telescope's OHS instrument, and the FMOS Spectrum Simulator described by Tamura and available at http://elvira.phyaig.dur.ac.uk/naoyuki.tamura/simulator.html. I discuss the improvements in data quality expected with FMOS.

2. SUBMILLIMETRE GALAXIES

The Submillimetre Common User Bolometer Array (SCUBA; Holland et al. 1999) on the James Clerk Maxwell Telescope (JCMT) has allowed us to make a great leap forward in our understanding of the Cosmic Submillimetre Background. Most of the background has been resolved into discrete sources (the so-called submillimetre galaxies, or SMGs), which appear to be dust-enshrouded starburst galaxies at high redshift. These objects have star formation rates as high as $\sim 1000\,\mathrm{M_\odot\,yr^{-1}}$, and are believed to have produced at least 25% of all the stars formed since the Big Bang, yet their counterparts are too faint to be discovered in optical surveys. Obtain accurate measurements of the obscured star formation, to be compared to the unobscured star formation determined from Lyman break galaxies, is important if we are to understand the overall star formation history of the Universe, and compare these two classes of object.

The optical faintness of the SMGs makes identification difficult, requiring interferometric measurements and accurate astrometry. Even then, finding the optical/infrared counterpart can be difficult, as in the case of HDF 850.1 (Hughes et al. 1998; Dunlop et al. 2004). Obtaining a spectroscopic redshift can be even more time-consuming, and attempts to use the radio–submm SED to constrain the redshift (e.g., Dunne, Clements, & Eales 2000; Yun & Carilli 2002; Hughes et al. 2002) have met with limited success. Chapman et al. (2003) have published the redshift distribution for ~ 100 SMGs, which peaks around $z = 2.4$. However, many of the spectra remain unpublished and there is little information on objects for which a redshift was not obtained, which could have a significant impact on the overall distribution.

Despite the relative success which Chapman et al. obtained with optical spectroscopy, the study of dusty objects usually suggests moving to as long a wavelength as practical. Notwithstanding the possibility of using the CO ladder to derive redshifts (which completely precludes the need for optical/IR identifications!), this suggests that near-infrared spectroscopy may prove successful.

The fibre density of FMOS is well-suited to the study of SMGs. An 850-μm flux density limit of 4 mJy gives 200 sources per FMOS field of view (Borys et al. 2003), which can be considered the 'critical density' for FMOS observations. At present, very little of the sky has been surveyed to this sort of depth; indeed, at a limit of 8 mJy, the largest completed survey covers 260 arcmin^2 (Scott et al. 2002), while the ongoing SHADES survey (http://www.roe.ac.uk/ifa/shades) will

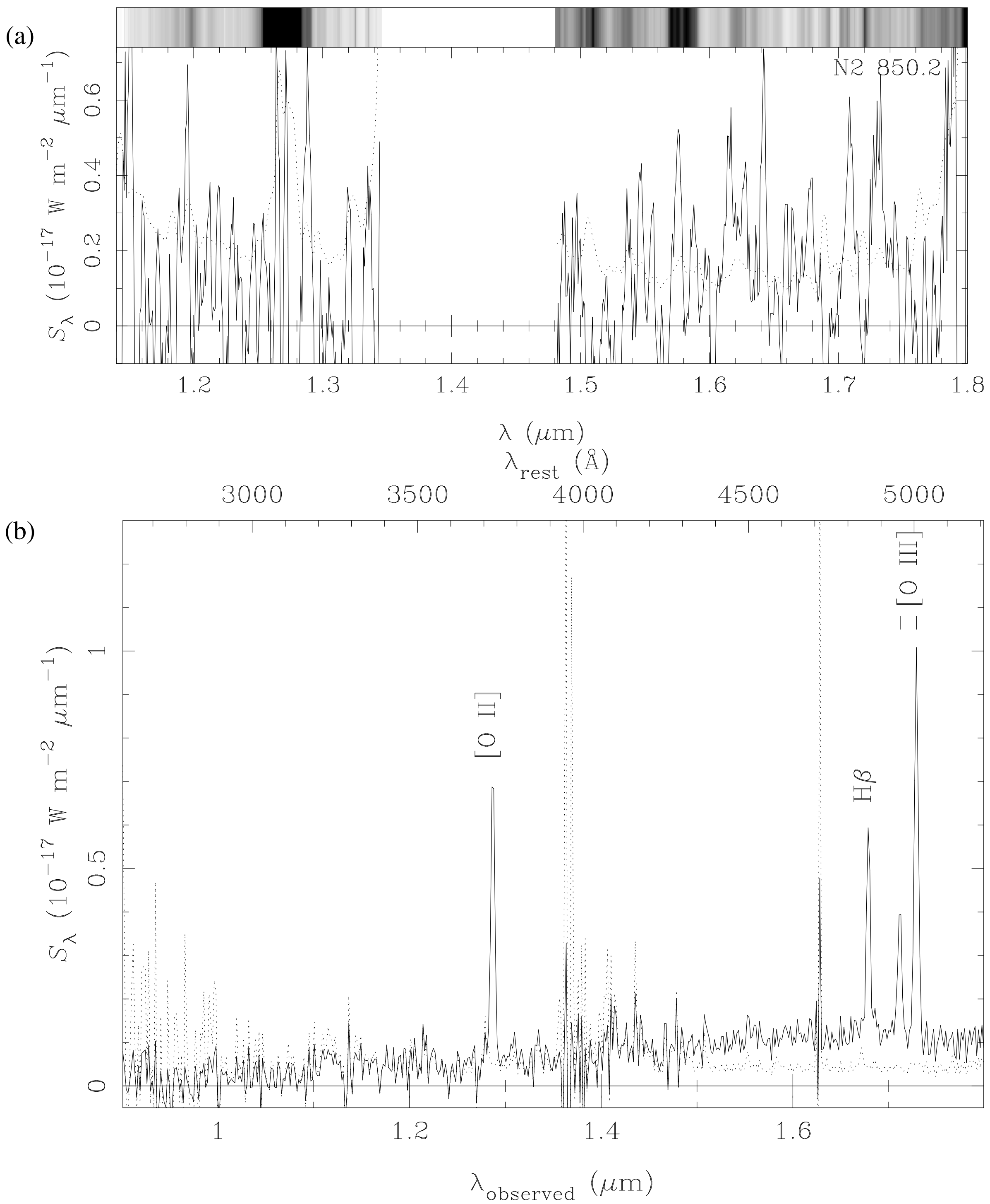

Figure 1: (a) OHS spectrum (from Simpson et al. 2004) of the SCUBA-selected galaxy ELAIS N2 850.2. The spectrum has been smoothed with a 5-pixel boxcar, and the dotted line shows the 1σ noise level of this smoothed spectrum. The grayscale along the top indicates the residual night-sky spectrum after passing through OHS. Four emission lines ([O II], Hβ, and the [O III] doublet) are detected at signal-to-noise ratios of between 2.3 and 3.0. (b) Simulated FMOS spectrum of the same source, assuming 7 hours of on-source integration. The emission lines are rather more obvious, and the continuum is well-detected.

cover $1800\,\mathrm{arcmin}^2$ in two fields (the SXDF and Lockman Hole) similar in size to the FMOS field of view, and suitable for initial study. However, in 2006, SCUBA-2 (Holland et al. 2003) is expected to be commissioned on the JCMT, which will use new technology to provide 'CCD-like' imaging of the sky at submm wavelengths and be able to map the sky up to $1000\times$ faster than SCUBA. Tens of square degrees could therefore be covered to an rms noise of $< 1\,\mathrm{mJy}$, providing plenty of targets for FMOS follow-up.

The expected results from an FMOS survey of SMGs can be readily determined from the FMOS simulators (these proceedings) provided the near-infrared spectroscopic properties of the targets are known. Unfortunately, there has been little published IR spectroscopy, and where strong emission lines are seen, they are indicative of an active galactic nucleus (e.g., ELAIS N2 850.4; Smail et al. 2003). While it has been suggested that AGN may be present in a large fraction of SMGs, in most cases they are not believed to be energetically dominant (Alexander et al. 2004), and so the properties of the starburst-dominated population are not well-determined.

In objects where Lyα emission is seen, it seems likely that the optical emission lines of [O II] and Hβ will be present, so the key test for determining how successful FMOS is likely to be comes from the objects without UV emission lines. Simpson et al. (2004) studied seven such objects, from the CUDSS and 8-mJy surveys (Eales et al. 2000; Scott et al. 2002) with OHS and had limited success. Plausible redshifts were obtained for three sources, although all were based on marginally-detected features with fluxes of $\sim 3 \times 10^{20}\,\mathrm{W\,m^{-2}}$ (an order of magnitude fainter than emission lines previously detected by near-IR spectroscopy of SMGs), at the limit of OHS's sensitivity.

While this may not appear very promising for future FMOS observations, there are several reasons to be optimistic. First, FMOS is a more sensitive instrument, with high multiplexing capabilities which will permit long integrations (tens of hours) to achieve sensitivities an order of magnitude better than Simpson et al. reached. Second, the measured line fluxes correspond to star formation rates of $\sim 20\,\mathrm{M_\odot\,yr^{-1}}$, already far lower than the estimates derived from the submm fluxes, and it seems implausible that all the star formation will be so heavily obscured as to not produce detectable emission lines at the $\sim 1\,\mathrm{M_\odot\,yr^{-1}}$ level. Third, the low resolution ($\lambda/\Delta\lambda \approx 200$) of the OHS observations reduced the sensitivity to features with widths of $\sim 300\,\mathrm{km\,s^{-1}}$, and made the subtraction of unmasked sky lines the dominant source of noise over much of the spectral range. The better resolution provided by FMOS should alleviate these difficulties, perhaps allowing absorption-line redshifts to be measured, provided sky subtraction does not affect the sensitivity. Finally, the use of fibres dramatically increases the sky area seen by each spatial pixel, and therefore makes dark current variations a less important source of systematic uncertainty.

The advantage of FMOS over OHS can be clearly seen in Fig. 1, where we compare the 2-hour OHS spectrum of ELAIS N2 850.2 with that expected from 7 hours with FMOS. It seems almost inconceivable that FMOS observations lasting one or two nights will fail to detect emission lines in almost every target. Furthermore, the good match in source and fibre density on the sky, coupled with the large field of view, means that FMOS will observe large areas more efficiently than any existing optical MOS instrument.

3. EXTREMELY RED OBJECTS

Extremely red objects (EROs) are defined on the basis of their optical (R or I) and near-infrared (H or K) colours, although the quantitative definition varies between authors by as much as a magnitude. These colours can be the result of either an evolved stellar population or younger, reddened stars, although in both cases the colours and magnitudes of the objects imply redshifts $1 \lesssim z \lesssim 2$. It is important to be able to separate the two classes since both are cosmologically interesting: the passive populations implies a relatively early epoch for massive galaxy assembly, and an earlier epoch of star formation; while the dusty starburst population may provide a large fraction of the overall star formation rate at $z \sim 1.5$, below the confusion limit of submillimetre surveys.

The red colours of EROs mean they are optically very faint, and spectroscopy has proven difficult, many authors concentrating on relatively blue (and hence optically brighter) objects (e.g., Cimatti et al. 2002). Instead, attempts have been made to classify them based on morphological and/or photometric properties although, worryingly, these methods seem to lack spectroscopic confirmation of their validity. Pozzetti & Mannucci (2000) suggest that the two classes of ERO can be distinguished in a colour–colour diagram, although the separation between them is not large and fewer than 10% of the sources from the Mannucci et al. (2002) sample, for example, are more than 3σ from the dividing line. While Mannucci et al. find that the two classes of EROs occur in roughly equal numbers, and claim that the uncertainty in assigning individual objects to a class should not affect the statistical nature of their result, Yan & Thompson (2003) find that disk galaxies outnumber spheroids by a factor of 2:1 in their *HST*-based morphological classification.

Clearly, spectroscopic classification is required, if only to confirm that either of these methods is valid. The SIRIUS imaging of the SXDF has produced a catalogue of relatively bright EROs which should produce relatively high signal-to-noise ratio spectra in 1–2 hours with OHS, although attempts to observe these in 2003 were unsuccessful due to poor weather. A smaller sample (4 objects) from the field of the wide-separation quasar pair PC 1643+4631A,B was observed in June 2001 (Cotter, Simpson, & Bolton 2004), although poor seeing and technical problems hampered the quality of data obtained.

These objects were selected from the catalogue of Haynes et al. (2002) to have $R - K > 5.5$, and are therefore redder than almost all the targets of Cimatti et al. (2002). Only one target (Fig. 2a) displayed any significant spectral features, namely an emission line at 15373 Å, which was identified as Hα at $z = 1.34$. The unresolved nature of the line implies little [N II] emission and therefore suggests that it is powered by star formation, rather than an AGN, and the star formation rate, uncorrected for reddening is $\sim\,20\,\mathrm{M_\odot\,yr^{-1}}$. Despite clearly belonging to the dusty starburst class of EROs, this object has a bulge-like morphology (an $r^{1/4}$-law is an excellent fit to the *HST* image) and lies extremely close to the dividing line in a colour–colour diagram (although it does fall just on the starburst side). Detailed fitting to the broad-band SED and OHS spectrum suggests that the true star formation rate is $\sim\,80\,\mathrm{M_\odot\,yr^{-1}}$, consistent with the upper limit at 5 GHz.

Clearly, FMOS can be expected to produce much higher quality data, and in Fig. 2b, a simulated spectrum of the ERO is shown. The FMOS spectrum provided additional information and therefore permits much deeper analysis than did the OHS data. For example, Hβ is detected, and therefore allows an estimate of the reddening from the Balmer decrement. Also, the Hα+[N II] blend is resolved, permitting a far more rigorous classification as AGN or starburst. Finally, the continuum is detected at much higher S/N, allowing spectral synthesis models to be constrained — the G-band and Ca H+K lines are detectable at the blue end of the spectrum in Fig. 2b.

Again, the source density of EROs is well-matched to the FMOS fibre arrangement, there being $\sim$ 200 per field of view at the $K \approx$ 19–20 magnitude limit, depending on the exact definition used (e.g., Yan & Thompson 2003). This is close to the limit of the UKIDSS Deep Extragalactic Survey (DXS; see http://www.ukidss.org), which will survey $\sim 35\,\mathrm{deg}^2$ to a point source limit of $K = 21$ (5σ), and so once again there will be a suitable sample available when FMOS is commissioned.

4. THE NEAR-INFRARED REDSHIFT DESERT

The 'redshift desert' is a term referring to the difficulty in obtaining redshifts from optical spectroscopy in the region $1 \lesssim z \lesssim 2$. At $z \gtrsim 1$, the [O II] emission line and 4000-Å break move into the OH forest, while Lyα does not enter the blue end of the spectrum until $z \sim 2$. Nod-and-shuffle techniques have made it possible to track [O II] to $z \sim 1.4$, while blue-sensitive spectrographs like LRIS-B enable Lyα to be picked up at $z \sim 1.8$, but there is still a region where redshift determination is extremely difficult. Sensitive near-infrared spectroscopy can help with this, since it can pick up the [O II] line and 4000-Å break as they are redshifted out of the optical region (and here, FMOS's coverage below 1 μm represents another advantage over many IR spectrographs). However, near-infrared spectroscopy has its own redshift desert in the range $2.7 \lesssim z \lesssim 3.0$. Beyond $z \approx 2.7$, Hβ is redshifted out of the H-band, while [O II] and the 4000-Å break lie in the region of poor atmospheric transmission between the J and H windows, and [O II] does not get redshifted into the H-band until $z \approx 3.0$ (and at these redshifts, Hα has moved out of the K-band). Although (unlike OHS) FMOS will take spectra of the regions of poor atmospheric transmission (except for a small region where the fibre bundle enters the spectrograph), this could substantially reduce the effectiveness of FMOS surveys of SMGs, which are believed to have a redshift peak of $z \sim 2.6$ (this is slightly larger than the median redshift found by Chapman et al., since their sample was radio-selected and is therefore slightly biased against the highest redshift sources). If there is sufficient S/N in the continuum, the 4000-Å break and G-band could provide redshifts for some sources in this region, depending on how well the continuum level can be determined at the blue end of the H-band.

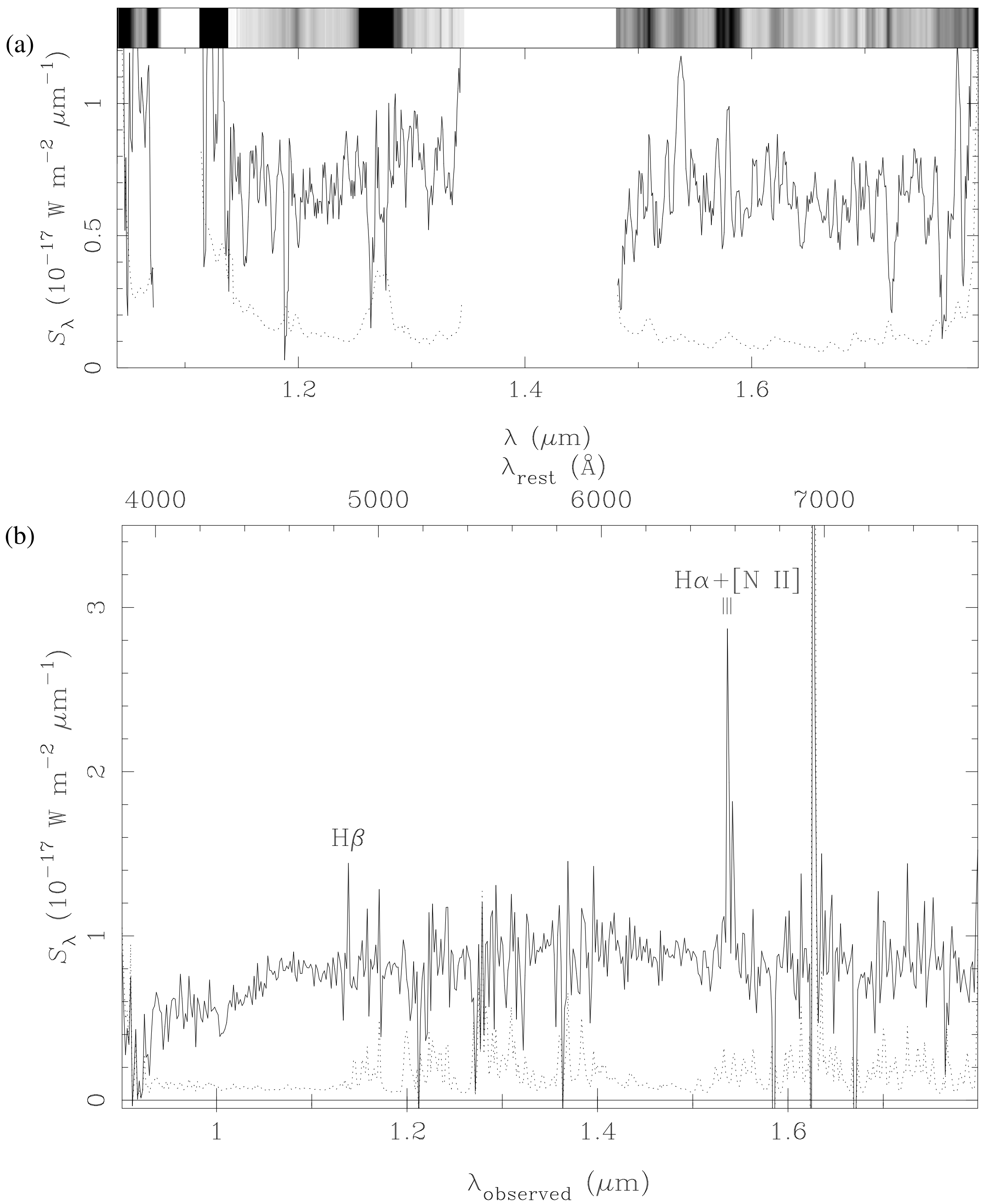

Figure 2: (a) OHS spectrum (from Cotter, Simpson, & Bolton 2004) of ERO J165404+46258, presented in the same manner as the spectrum of Fig. 1a. (b) Simulated FMOS spectrum of the same source, assuming 7 hours of on-source integration.

5. SUMMARY

Clearly, FMOS has the potential to greatly improve the quality of near-infrared spectroscopy obtainable for faint sources. Both submillimetre galaxies and extremely red objects have the right fluxes and source densities on the sky, and suitably sized samples should become available on the right time scales for exploitation with FMOS. Even relatively modest allocations of a few nights will be sufficient to dramatically improve the data and our understanding of these two classes of source.

Assuming that the various components perform to specification, the limiting factor for its ultimate sensitivity is likely to come from the accuracy with which the residual sky can be subtracted. It is important that different modes of operation, including beam-switching, are investigated during the initial commissioning period, to determine the best way to obtain the high sensitivities required to achieve the scientific goals discussed above.

Roll on FMOS!

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