Science with the re-baselined European Extremely Large Telescope

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ABSTRACT

The modifications to the European Extremely Large Telescope (E-ELT) baseline design were accompanied by an evaluation of their impact on science. We will present the conclusions of this evaluation.

The Design Reference Mission served as the benchmark for the evaluation. None of the modifications critically affect the Science Case. In particular, the full instrumentation suite can still be implemented allowing for the full foreseen suite of science cases. The largest impact is induced by the reduced diameter. For a large fraction of the science cases this can be offset by increasing the exposure times by ~20% to 34%. Where spatial resolution is the limiting factor, the limits have to be reduced by 9%.

The exoplanet case deserves a special mention: two of the three components of this case (detection of Earth twins by the radial velocity method, and characterisation of the atmospheres of transiting planets) are unaffected; for the third component (direct imaging of Earth-like planets) the same results as for the original baseline can be achieved, but only at 20% smaller distances.

Overall, all of the major science cases of the E-ELT can essentially be maintained.

Keywords: Extremely Large Telescope, E-ELT, Science Case, ESO

1. INTRODUCTION

After its detailed design phase the European Extremely Large Telescope (E-ELT) project responded to challenges in the areas of cost and risk by proposing a revised baseline design for the telescope. This revision is described in detail elsewhere in these proceedings[1]. In this contribution we evaluate the impact of the new telescope baseline on the E-ELT's scientific capabilities, and evaluate the consequences for the E-ELT Science Case[2]. In particular, we will compare the scientific capabilities of the original design for the E-ELT (referred to as the 42 m E-ELT) to those of the revised design (referred to as the 39 m E-ELT, following the TMT convention).

In the following we list those elements of the design revision that we consider potentially relevant for the E-ELT's scientific capabilities:

1. Reduced diameter: In the new design two outer rings of segments were removed from the primary mirror, and an inner one added, resulting in a smaller primary mirror. For comparison and ease of reference Table 1 lists the effective collecting area, the corresponding diameter of a filled disk, the largest diameter that encloses only glass, and the circumscribing diameter for the 39 m and 42 m versions of the E-ELT, together with the corresponding values for the GMT and TMT. The layout and dimensions of the primary mirror of the 39 m E-ELT are shown in Figure 1.
2. Loss of the gravity invariant focus: The new design no longer includes an instrument station below one of the Nasmyth platforms. An instrument placed at this station would have received the light from the telescope from above, so that its rotation axis would have coincided with the gravity vector, providing greater stability than when located on the Nasmyth platform itself.
3. Smaller Nasmyth platforms: In the new design the size of the Nasmyth platforms has been reduced from 14.6 m × 29.0 m to 11.8 m × 29.0 m, so that in principle less room is available for instruments.
4. Gain in schedule: Due to the significant reductions in risk and cost of the new design it is estimated that first light of the 39 m E-ELT can occur about 2 years earlier compared to the original design.

The diameter of the telescope determines both its diffraction-limited spatial resolution as well as its photon collecting power. Hence it is one of the key parameters that limit the achievable quality of data collected with the E-ELT. Thus, of the changes listed above, the reduction of the telescope's diameter certainly has the most significant impact on the E-ELT's scientific capabilities. In the next section we provide an overview of how different science cases may depend on the diameter of the telescope, and attempt to quantify the overall science loss engendered by its reduction when moving from the 42 m to the 39 m E-ELT.

Table 1. Collecting areas and various relevant diameters of the 39 m and 42 m E-ELT designs, the GMT, and the TMT.

	39 m E-ELT	42 m E-ELT	TMT	GMT
effective collecting area*	978 m^2	1223 m^2	655 m^2	382 m^2
corresponding diameter	35.3 m	39.5 m	28.9 m	22.1 m
largest fully filled diameter	37.0 m	41.3 m		
circumscribing diameter	39.1 m	43.2 m	30.0 m	25.4 m

*The E-ELT numbers in this line ignore the gaps between segments.

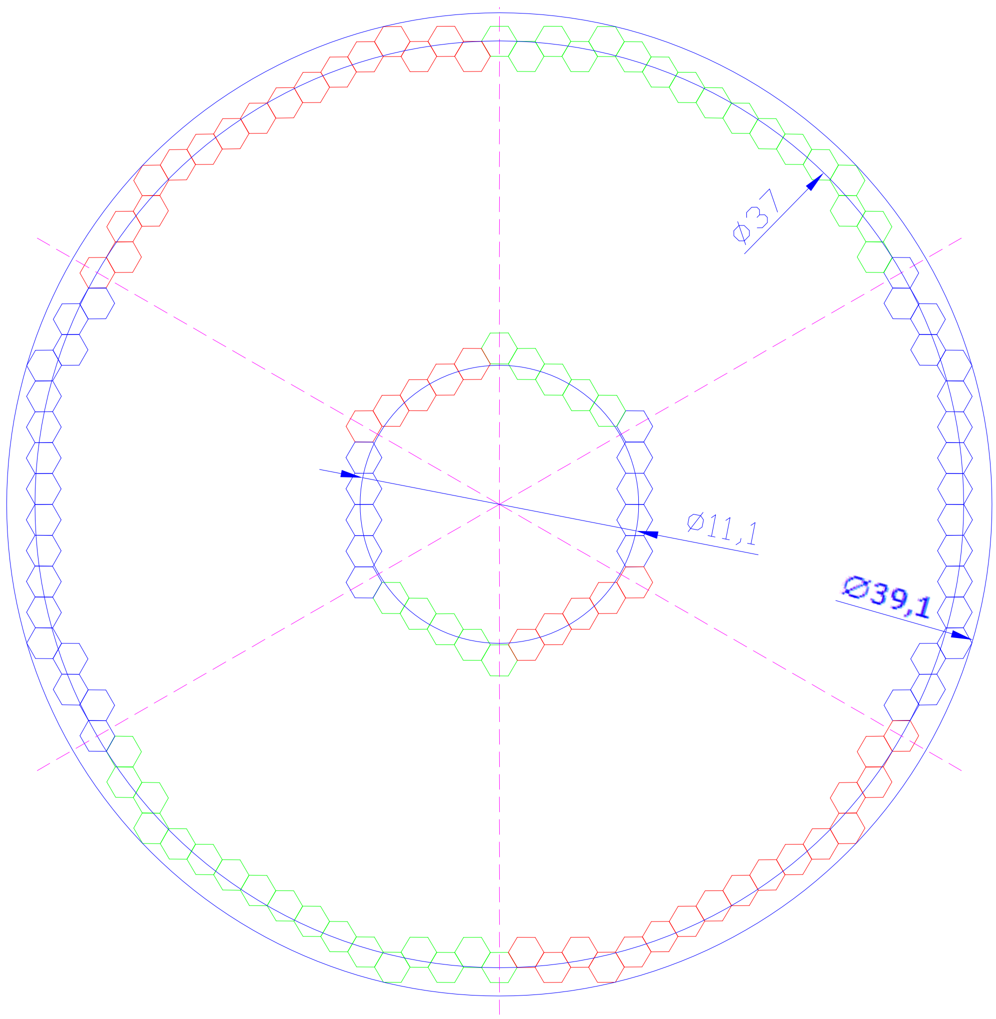

Figure 1. Layout and dimensions of the primary mirror of the 39 m E-ELT.

2. IMPACT OF REDUCED DIAMETER ON SCIENCE

The diameter[†] of the primary mirror (D) is the most fundamental and most important characteristic of any telescope system, but particularly for an adaptive optics assisted telescope, as it determines both its diffraction-limited spatial resolution ($\propto D^{-1}$) as well as its photon collecting power ($\propto D^2$). Depending on the scientific goal as well as the observational and astrophysical circumstances these properties may combine differently, leading to many different ways in which a given science case may depend on D. In this section we attempt to categorize these and hence to provide a systematic overview of the different ways in which a given science case may be affected by going from the 42 m to the 39 m E-ELT. However, since the E-ELT will be an extremely versatile instrument that can be applied to a vast range of different astrophysical questions, we must abandon any claim to completeness.

At the highest level we may distinguish between the following three classes of science cases: (i) cases where science is irretrievably lost by reducing the telescope diameter; (ii) cases where the loss of telescope diameter can be compensated for by increasing the observing time or adjusting some other observational parameter; (iii) cases that are not affected by the reduction of the telescope diameter at all. We now discuss each of these classes in turn.

Those cases where science is irretrievably lost by reducing the telescope diameter naturally provide some of the strongest drivers for building an E-ELT in the first place. This class can be sub-divided into two categories: (a) cases that rely principally on the spatial resolution of the E-ELT and (b) cases where the available integration time is limited by external factors.

The unique spatial resolution of the E-ELT is one of its defining characteristics and hence it is not surprising that many of the science cases that have been proposed for the E-ELT aim to exploit this feature. All cases that require the E-ELT's resolution to disentangle their targets from other (apparently) nearby sources will be forced to adopt less demanding goals for the 39 m E-ELT than originally envisaged for the 42 m E-ELT. This encompasses a vast range of science cases, and prominent examples include the direct detection of exoplanets (all high contrast imaging applications depend particularly strongly on D), the study of the resolved stellar populations of other galaxies, as well as studies of the supermassive black holes and their environments in the centre of our own and other galaxies.

The other sub-category in this class contains cases where the observing time cannot arbitrarily be extended, even in principle. This includes observations of non-recurring transient events, such as GRBs or supernovae, and recurring events with very long periods, such as some eclipses or transits. Observations limited by the rotation or oscillation period, or some other timescale inherent to the target are also affected. In all of these cases the reduction of D will lead to a loss of S/N which cannot be compensated for by increasing the integration time.

The second class of science cases contains those that are limited by the S/N that is achievable on their targets, and where the S/N is not dominated by (D-independent) astrophysical error sources or systematic uncertainties (astrophysical, instrumental, or otherwise). To a large extent these cases principally exploit the other key characteristic of the E-ELT, namely its unique photon collecting power (although in some circumstances the resolution also plays a role in limiting the achievable S/N, see Table 2). The feature that is common to all of these cases, and which sets them apart from those in the first class, is that a decrease of D can be compensated for by increasing the observing time in order to achieve the same result with the 39 m as with the 42 m E-ELT. Again, this class encompasses a vast range of science cases. Prominent examples include most studies of high redshift galaxies, investigations of the stellar populations in our own galaxy, and the search for possible variations of fundamental constants.

Note that although it is possible for the science cases in this class to achieve the same results with the 39 m as with the 42 m E-ELT by increasing the observing time, it is not necessarily clear that one would actually want to do so. The reason is of course that the total amount of observing time on the E- ELT is limited: increasing the observing time for some cases must necessarily result in less time being available for others, ultimately leading to a smaller total number of

[†] In this section, for the sake of simplicity and brevity, we will largely disregard the distinction between the various diameters listed in Table 1, and simply refer to 'the diameter'.

programmes being carried out. When going from the 42 m to the 39 m E-ELT we are thus faced with a trade-off (which must be evaluated case-by-case) between being able to carry out a smaller number of different programmes on the one hand, and accepting less advanced results for individual cases on the other.

Finally, the third class of science cases contains those cases that are limited by (*D*-independent) astrophysical error sources or systematic uncertainties, or where the reduction of *D* can be compensated for by adjusting parameters that have essentially no impact on the science. We stress that we are only referring to cases that are quasi-independent of *D* for the specific regime we are concerned with here, i.e. when going from the 42 m to the 39 m E-ELT. (Cases that are quasi- independent of *D* for much larger ranges of *D* are of course ill-suited to providing strong science drivers for the E-ELT in the first place.) This class does not encompass many cases, but one prominent example is the detection of low-mass exoplanets using the radial velocity method.

In summary, when going from the 42 m to the 39 m E-ELT the science cases of the three classes described above are affected in the following ways: for each individual case in class (i) we must accept that we will be able to achieve less with the 39 m E-ELT than what would have been possible with the 42 m E-ELT, without any possibility to redress these losses. For the science cases in class (ii) we have, at least in principle, the possibility to trade-off the scientific losses suffered by individual cases against a reduction of the overall scope of the E-ELT's total programme by re-distributing observing time. Finally, science cases of class (iii) are not affected by going from the 39 m to the 42 m E-ELT.

The above discussion was entirely qualitative. However, for the science cases of class (ii) and some of the cases in class (i) we can also attempt a categorisation based on the quantitative dependence of a science case on *D*. Again, due to the wide range of science cases we cannot possibly hope to be complete in this exercise. Nevertheless, in Table 2 we list how important observational parameters scale with *D* for a variety of frequently encountered observational circumstances. These parameters are: the S/N that can be achieved for a given object flux and integration time; the integration time required to achieve a given S/N for a given object flux; and the limiting object flux down to which a given S/N can be achieved in a given integration time.

Defining the scientific efficiency of the E-ELT as the inverse of the observing time required to achieve its science goals, we can see from Table 2 that it may scale as strongly as D^4, depending on the observational circumstances. Indeed, in high contrast imaging applications, the achievable science result usually depends on *D* even more strongly. Figure 2 illustrates these different scaling laws.

The overall loss of scientific efficiency resulting from the reduction of the E-ELT's diameter depends of course on how its observing time will be distributed among science cases following different scaling laws. This is impossible to know a priori, but it is reasonable to assume that the E-ELT will spend much of its time doing D^2 and D^4 science, resulting in an overall loss of efficiency in the range of 20–34%[‡].

In addition to assessing the overall loss of scientific efficiency, we may also ask whether any individual science cases are rendered completely unfeasible by the reduction of the E-ELT's diameter, in the sense that the diameter is now below some critical threshold value for these cases. We have investigated in detail the impact of the diameter's reduction on two of the most demanding key science areas (Exoplanets and Fundamental Physics), and we have undertaken a less detailed survey of the impact on the science cases studied by the E-ELT Design Reference Mission. A full discussion of the result of this analysis is beyond the scope of this contribution. In summary, we find that of all the major science cases for the E-ELT, the one that is most severely affected by the reduction of the telescope's diameter is the direct imaging of Earth-analogue exoplanets. Nevertheless, our overall conclusion is that none of the major science cases for the E-ELT must be completely abandoned, and that, on the whole, the E-ELT Science Case[2] remains intact and does not require any major revision.

[‡] $20\% = 1 - (978\ \text{m}^2 / 1223\ \text{m}^2)$; $34\% = 1 - (39.1\ \text{m} / 43.2\ \text{m})^2\ (978\ \text{m}^2 / 1223\ \text{m}^2)$.

Table 2. This table shows how the S/N, the integration time t_{int} and the limiting flux f_{lim} scale with telescope diameter in a range of different observational situations.

		Point source	Extended source	Extended source (per res. element)[1]
Background photon noise limited	Seeing limited	$S/N \propto D$ $t_{int} \propto D^{-2}$ $f_{lim} \propto D^{-1}$		
	Diffraction limited	$S/N \propto D^2$ $t_{int} \propto D^{-4}$ $f_{lim} \propto D^{-2}$	$S/N \propto D$ $t_{int} \propto D^{-2}$ $f_{lim} \propto D^{-1}$	$S/N \propto D^0$ $t_{int} \propto D^0$ $f_{lim} \propto D^0$
Object photon noise limited	Seeing limited	$S/N \propto D$ $t_{int} \propto D^{-2}$ $f_{lim} \propto D^{-2}$		
	Diffraction limited	$S/N \propto D$ $t_{int} \propto D^{-2}$ $f_{lim} \propto D^{-2}$		$S/N \propto D^0$ $t_{int} \propto D^0$ $f_{lim} \propto D^0$
Read-out noise limited[2]	Seeing limited	$S/N \propto D^2$ $t_{int} \propto D^{-2}$ $f_{lim} \propto D^{-2}$		
	Diffraction limited	$S/N \propto D^2$ $t_{int} \propto D^{-2}$ $f_{lim} \propto D^{-2}$		$S/N \propto D^0$ $t_{int} \propto D^0$ $f_{lim} \propto D^0$
Crowding limited	Diffraction limited	$S/N \propto D$ $t_{int} \propto D^0$ [3] $f_{lim} \propto D^{-2}$		

Notes:

[1]In this column f_{lim} denotes a surface brightness.

[2]In this row we assume that the number of pixels per resolution element does not depend on D.

[3]This is only an approximation, the exact relation depends on the stellar population.

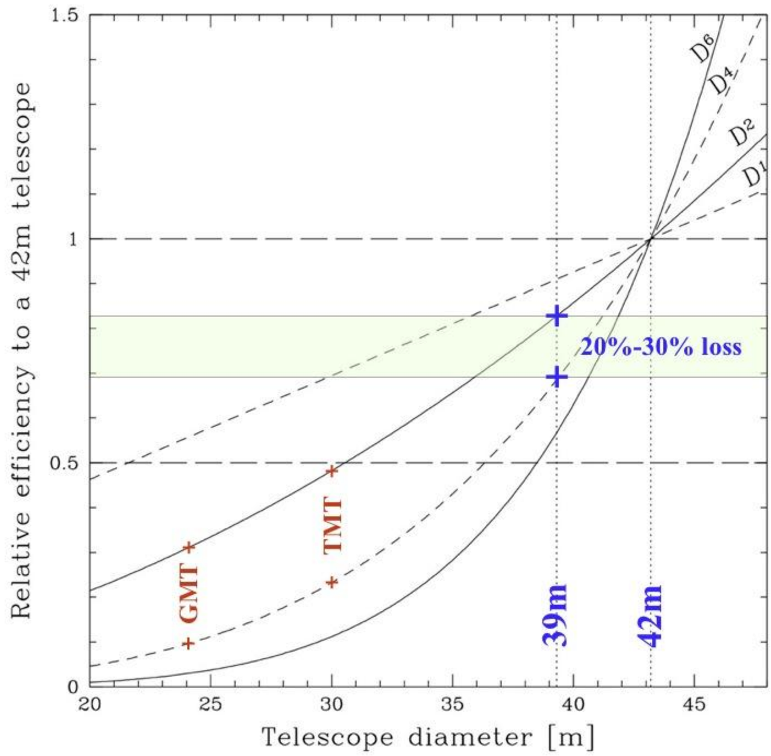

Figure 2. Scientific efficiency of the E-ELT relative to the 42 m case as a function of telescope diameter.

3. IMPACT OF OTHER MODIFICATIONS ON SCIENCE

3.1 Loss of Gravity Invariant Focus

The original 42 m design included a so-called gravity invariant focal station below one of the Nasmyth platforms. At this station the light from the telescope is delivered from above such that the focal plane is horizontal. This allows an instrument at this station to rotate around an axis that is parallel to the gravity vector, greatly reducing the need to compensate for flexure inside the instrument.

The only tool we currently have available to assess the impact of the loss of this focal station in the new 39 m design on the E-ELT's scientific performance is to refer to the phase A instrument concept studies that were carried out as part of the E-ELT instrument study plan between 2007 and 2010[3]. Of these nine phase A instrument studies only the near-IR multi-IFU spectrometer concept EAGLE[4] planned to occupy the gravity invariant focal station. Furthermore, it is currently unclear to what extent EAGLE actually requires the gravity invariant focal station, or whether the main science cases covered by EAGLE (the assembly of high redshift galaxies, stellar archaeology) could also be delivered by an instrument located on the Nasmyth platform. A preliminary study by the EAGLE consortium concluded that EAGLE could indeed be moved to the straight-through Nasmyth focal station without impacting its performance. This issue is not yet fully resolved and will require further study.

We also note that two other concepts (MICADO[5] and SIMPLE[6]) have developed gravity invariant solutions for the Nasmyth platform.

We hence reach the provisional conclusion that the loss of the gravity invariant focal station has little to no impact on the scientific performance of the E-ELT.

3.2 Smaller Nasmyth Platforms

The Nasmyth platforms of the 39 m E-ELT will measure 11.8 m × 29.0 m, which corresponds to a reduction of 2.8 m in the "radial" direction compared to the 42 m E-ELT. However, the size of the pre-focal station has also been reduced significantly in the new design. As a result, the smaller Nasmyth platforms of the new design can still accommodate the same number of instruments (of the same size) as in the original 42 m design. Figure 3 shows a possible configuration of the instruments on the smaller platforms of the new design. Hence we do not consider the reduction of the size of the Nasmyth platforms to have any impact on the scientific performance of the E-ELT.

3.3 Gain in Schedule

It is estimated that first light of the 39 m E-ELT can occur about two years earlier compared to the original design, directly addressing the explicit goal formulated by Council that the E-ELT should be built on a competitive time scale. However, beyond this the accelerated schedule has two important positive consequences for E-ELT science.

First, we know from past experience that unlocking previously inaccessible parameter space will lead to unforeseen discoveries, many of which will be made in the first years. We expect that this will also apply to the ELTs. Indeed, this is a point of emphasis in the E-ELT Science Case[2]. Being the first ELT will therefore maximise the scientific impact the E-ELT will have on astronomy, and the accelerated schedule reduces the risk of one of the competing projects (TMT and GMT) arriving on sky before the E-ELT.

Secondly, we recall that the E-ELT Science Case also placed considerable emphasis on the additional science that will flow from the complementarity of data from the E-ELT and other facilities such as ALMA and the JWST. These synergies will be best exploited if the facilities are contemporaneous. Given that the JWST has a guaranteed mission lifetime of only five years, it is clear that optimal teamwork between the E-ELT and JWST requires the E-ELT to be on sky while the JWST is operating – the JWST launch is currently foreseen in 2018. This goal is expedited by the accelerated schedule of the 39 m design.

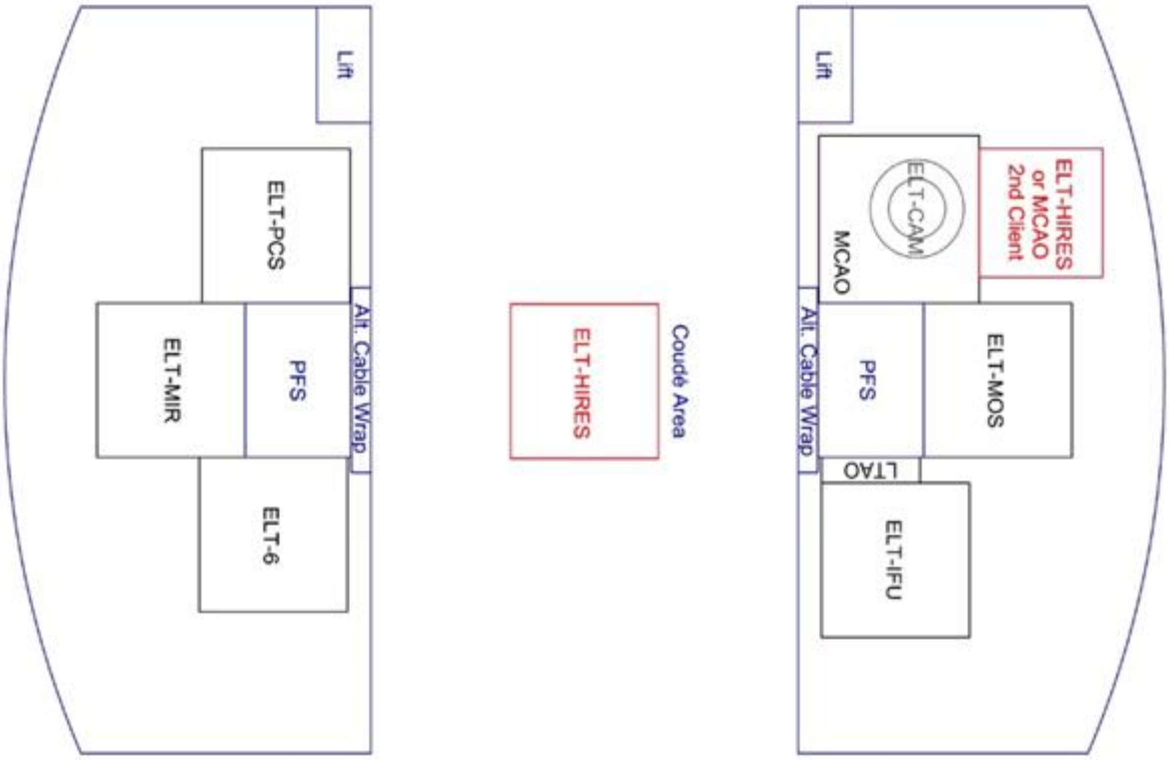

Figure 3. Possible arrangement of the instruments on the Nasmyth platforms and in the coudé room.

4. IMPACT ON INSTRUMENTATION

We first of all note that the new 39 m design of the E-ELT does not include any changes to the E-ELT instrumentation plan. In particular, the instrumentation budget, the number of first-light instruments and the number of first-generation instruments all remain unchanged.

Secondly, we note that no element of the existing instrumentation plan is rendered unfeasible or no longer sensible by the changes in the design.

Thirdly, as we have seen in Sections 2 and 3 the impact of the changes in the design on the science have not let to a major revision of the E-ELT Science Case[2]. Consequently, the instrumentation demands and priorities set by the Science Case remain unaltered.

We hence conclude that the adoption of the 39 m design has no impact on E-ELT instrumentation plans.

5. CONCLUSIONS

We have evaluated the impact of the change of the E-ELT's baseline design on the E-ELT's scientific capabilities and on its science case. Not surprisingly, the aspect of the new design that has the largest impact on science is the reduced size of the primary mirror. However, for a large number of science cases this loss of diameter can be offset by increasing the exposure times by ~20% to 34%. Inevitably though, where spatial resolution is the limiting factor, the limits of what can be achieved have to be reduced by 9%. Nevertheless, as a result of our analysis we conclude that this reduction does not render any of the E-ELT's major science cases completely unfeasible. Furthermore, the other modifications of the design were determined to have little to no adverse impact on the E-ELT scientific capabilities. Finally, we note that the new design did not have any impact on the E-ELT instrumentation plan.

We thus conclude that, on the whole, the E-ELT Science Case[2] remains intact and does not require any major revision on account of the changed baseline design.

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