

CODEX

Luca Pasquini^{*a}, Stefano Cristiani^b, Ramon Garcia Lopez^c, Martin Haehnelt^d, Michel Mayor^e, Jochen Liske^a, Antonio Manescau^a, Gerardo Avila^a, Hans Dekker^a, Olaf Iwert^a, Bernard Delabre^a, Gaspare Lo Curto^a, Valentina D'Odorico^b, Paolo Molaro^b, Matteo Viel^b, Eros Vanzella^b, Piercarlo Bonifacio^b, Paolo Di Marcantonio^b, Paolo Santin^b, Maurizio Comari^b, Roberto Cirami^b, Igor Coretti^b, Filippo Maria Zerbi^f, Paolo Spanò^f, Marco Riva^f, Rafael Rebolo^c, Garik Israelian^c, Artemio Herrero^c, María Rosa Zapatero Osorio^c, Fabio Tenegi^c, Bob Carswell^d, George Becker^d, Stéphane Udry^e, Francesco Pepe^e, Christophe Lovis^e, Dominique Naef^e, Miroslava Dessauges^e, Denis Mégevand^e

^aEuropean Southern Observatory, Karl Schwarzschildstr. 2, D-85748 Garching, Germany;

^bINAF - Osservatorio Astronomico di Trieste, Via Tiepolo 11, 34143 Trieste, Italy;

^cInstituto de Astrofísica de Canarias, Via Lactea s/n, E-38200 La Laguna, Tenerife, Spain;

^dInstitute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK;

^eUniversité de Genève, Observatoire Astronomique, 51 ch. des Maillettes, 1290 Versoix, Switzerland;

^fINAF - Osservatorio di Brera, Via Bianchi 46, I-23807 Merate, Italy;

ABSTRACT

CODEX is the proposed ultra-stable optical high-resolution spectrograph for the E-ELT, which will use novel Laser Comb calibration techniques and an innovative design to open a new era for precision spectroscopy. With its unique combination of light-collecting power and precision, CODEX will make it possible to directly measure the acceleration of the Universe by monitoring the cosmological redshift drift of spectroscopic features at cosmological distances. CODEX will also allow the assembly of the first sizeable sample of earth-like planets in the habitable zones of their stars with the radial velocity technique. CODEX will take this technique to the level of cm/sec radial velocity stability – a factor of about 20 improvement compared to current instruments. These are two of the scientific results anticipated for CODEX, which will be complemented by a wide range of spectacular science in stellar, galactic and extra-galactic Astronomy as well as Fundamental Physics. All the critical technology items are available or (as for the Laser Frequency Comb) are in an advanced state of testing. CODEX is located at the E-ELT coudé focus that will cover the visible range from 370 to 710 nm and provide a resolving power $R \sim 120000$ with an aperture of 0.8 arcseconds in the sky.

Keywords: E-ELT, High Resolution Spectroscopy, Precise Doppler measurements

1. SCIENCE WITH CODEX

The E-ELT project is designed to sustain the internationally leading role of Europe in ground-based Astronomy in the imminent transition from 10m to 30-50m apertures. While instruments geared towards the infrared (IR) will exploit the advantages of partially reaching the diffraction limit, photon-hungry high-precision spectroscopy will particularly benefit from the enormous light collecting power of the E-ELT. The substantially increased photon flux together with the huge advances in precision and stability in spectrograph building to be realized in CODEX will enable some new, truly spectacular science. CODEX will facilitate progress across a range of the burning science questions of our time. The two most spectacular scientific results anticipated for CODEX are probably the direct detection of the expansion of the Universe and the detection of earth-like twins.

We will not have the space and resources here to present the wide range of exciting problems CODEX will be able to tackle in detail. We have thus concentrated on five “Show Cases” which highlight the abilities of CODEX. These Show Cases cover a wide range of subject areas and technical demands on the spectrograph in order to aid in the necessary trade-offs in the spectrograph design.

*lpsquin@eso.org; phone + 49 89 32006792; <http://www.eso.org>

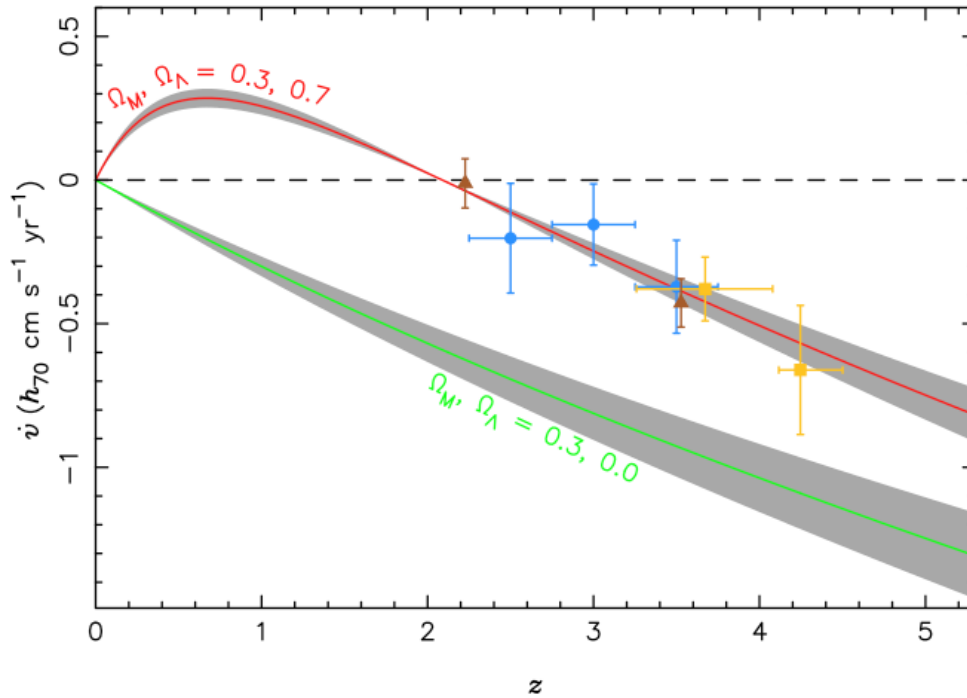


Figure 1: Monte-Carlo simulations of three different implementations of a redshift drift experiment as outlined in the text. Plotted are values and errors of the “measured” velocity drift \dot{v} , expected for a total experiment duration of $\Delta t_0 = 30$ yr, a total integration time of 4000 h and for standard cosmological parameters ($h_{70} = 1$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$).

- **A direct measurement of the accelerating expansion of the Universe - Detecting and measuring the cosmological redshift drift of the Lyman-alpha forest:** The cosmological redshifts of spectroscopic features originating at large distances are the signature of an expanding Universe. As the expansion rate changes with time, the change is expected to be mirrored by a corresponding change in redshift. This is a very small effect, but should become measurable with CODEX if the collective signal in a large number of absorption features is monitored. The most favorable target is the multitude of absorption features making up the Ly- α forest in QSO absorption spectra¹.
- **Detection of Earth twins in the Habitable Zone of solar-type stars:** The search for extra-solar earth-like planets which at least in principle could sustain life similar to that on our planet catches the imagination of scientists as well as that of the general public. The required accuracy for radial velocity searches to detect rocky planets in the habitable zone is 10 cm/sec, and this will be in reach of the proposed HARPS²-like spectrograph ESPRESSO³ for the VLT. The 2 cm/sec accuracy of CODEX constitutes a factor of about 20 improvement compared to current instruments. With this accuracy it will be possible to assemble and study sizeable samples of earth-like planets in the habitable zone of their parent stars.
- **Galactic Archaeology: Unravelling the assembly history of the Milky Way with nucleochronometry:** How galaxies assembled and came to look the way they do is another of the big questions in Astronomy. Much has been learned in this respect from our own Galaxy, which we can study in so much more detail than other galaxies. CODEX will take the sensitivity with which weak features of rare isotopes in stellar spectra can be studied to new limits. This should turn nucleochronometry - the equivalent of dating materials on the Earth using radioactive nuclides - into an accurate quantitative astronomical tool. The resulting precise age determinations of stars should lead to substantial progress in unravelling the assembly history of the Milky Way.

- Probing the interplay of galaxies and the Intergalactic Medium from which they form:** The formation of the first autonomous sources of radiation, stars and black holes, will have led to the heating, reionization and pollution of the intergalactic medium (IGM) with metals. The sensitivity of CODEX to the expected weak absorption features of trace amounts of metals in the low-density IGM thus opens a window into this important period in the history of the Universe. CODEX will enable the study of the interplay of galaxies and the intergalactic medium from which they form in unprecedented detail.
- Testing Fundamental Physics - Taking the test of the stability of fundamental constant to new limits:** The values of many fundamental constants in physics have little if any theoretical explanations. Fundamental constants have thus long been speculated to vary in space or time or both. The discovery of such variations would be a revolutionary result and would lead to the development of new Physics. The current evidence for small variations of the fine structure constant on cosmological timescales from studies of QSO absorption spectra is intriguing but rather controversial. CODEX will take tests of the stability of fundamental constants to greatly improved new limits.

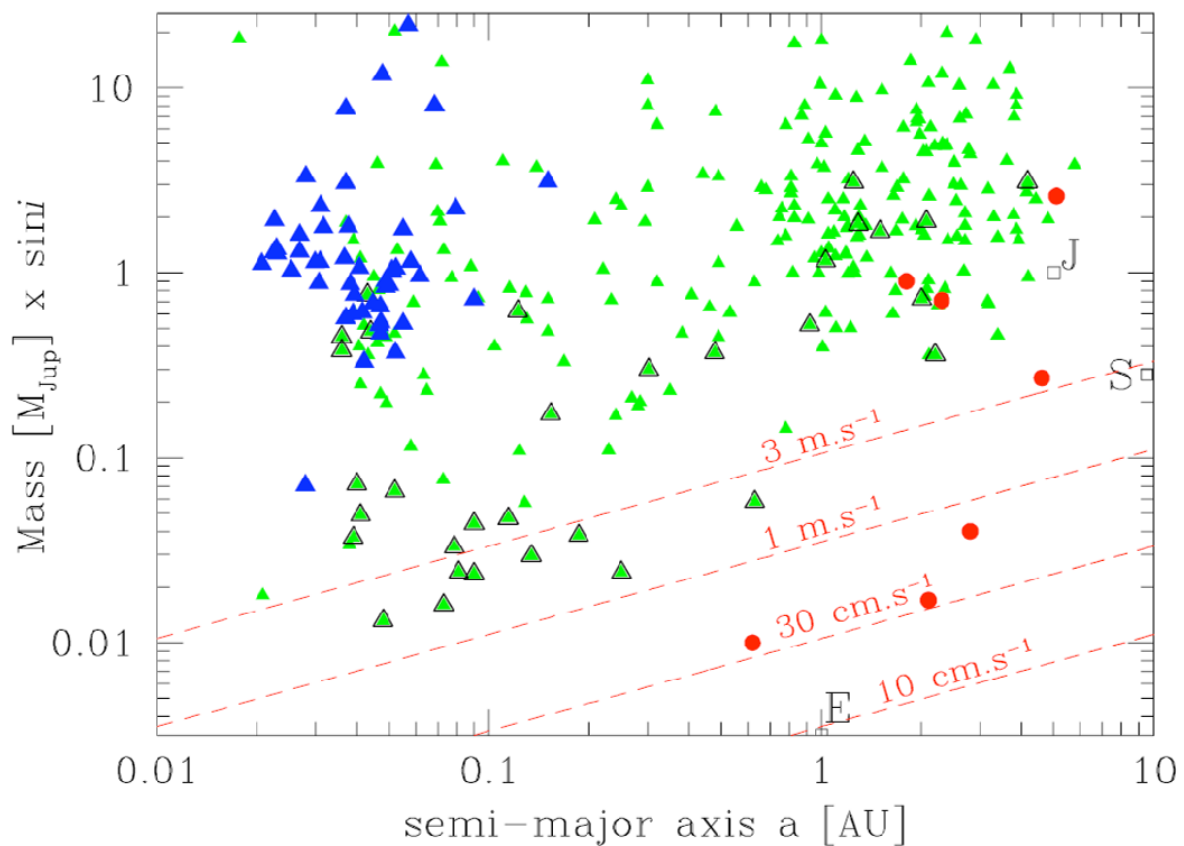


Figure 2: Mass-separation diagram of 300 known exoplanets. Green triangles refer to exoplanets found by radial velocities. Blue triangles refer to transiting ones. The circles refer to exoplanets found by microlensing. The bold green triangles correspond to exoplanets discovered with HARPS. Lines of radial-velocity semi-amplitude of 3, 1, 0.3 and 0.1 m/sec are shown, assuming a $1M_{\odot}$ primary star.

Despite its ambitious precision and stability goals, CODEX will be a versatile general purpose high-resolution optical spectrograph. Past attempts to predict ahead of time what will be the most exciting science produced by instruments opening up new regions of discovery space have generally failed. We obviously hope that this will hold for CODEX as well.

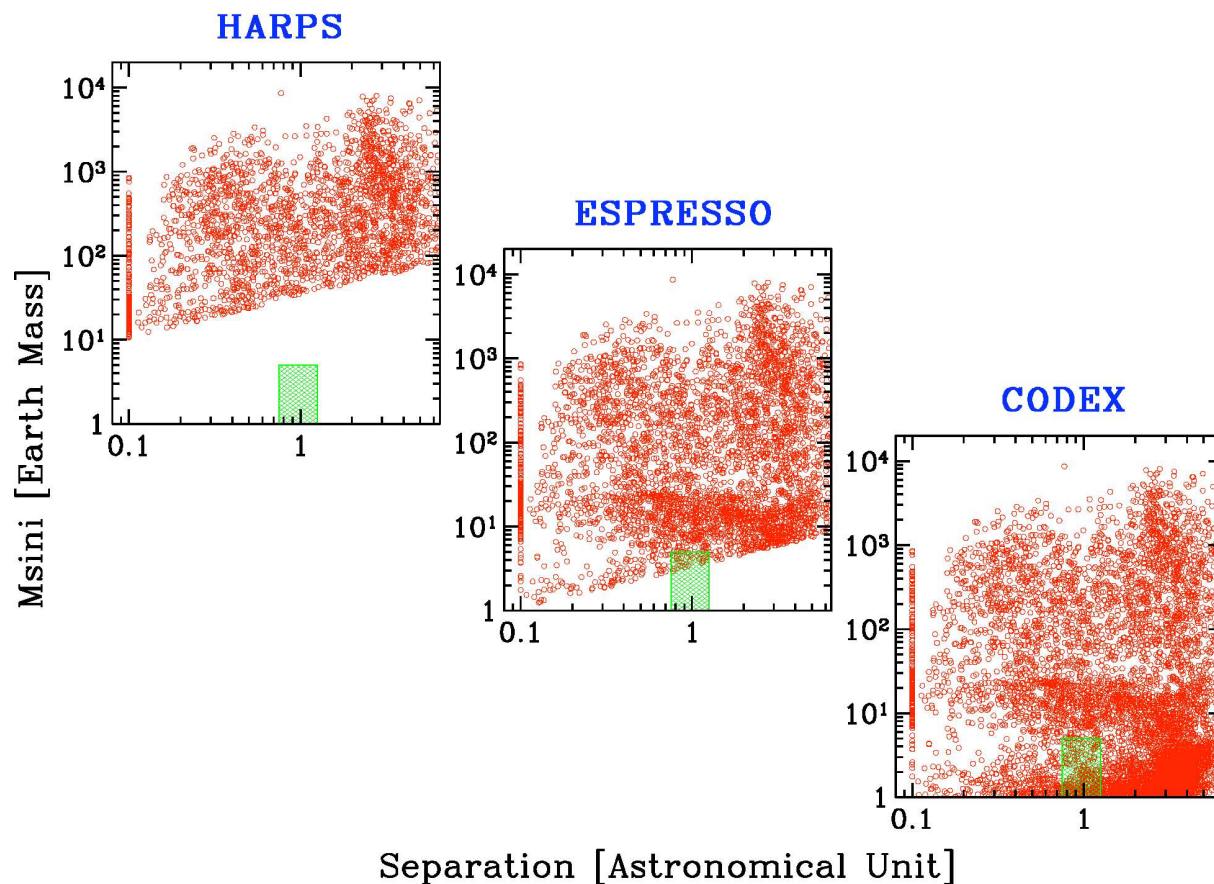


Figure 3: Expected planet population detected by Doppler spectroscopy, after applying observational limits for radial velocity measurements, with the HARPS/3.6m (precision of 1 m/sec; left), ESPRESSO/VLT (precision of 10 cm/sec; middle) and CODEX/E-ELT (precision of 1 cm/sec; right) spectrographs. For the detection criterion it was assumed that the RV semi-amplitude is equal to twice the precision. The figures are based on the predictions of the planet formation models of planetary populations for solar-mass stars by the Bern group. Limitations due to stellar noise are not taken into account in these estimates. A spectrograph like CODEX is required to detect Earth-like planets in the habitable zone of solar-type stars (colored rectangular area) and we can expect to detect sizeable samples of such planets.

1.1 CODEX in relation to other instruments and facilities

One of the most prominent areas of synergy between CODEX and other instruments and facilities is exoplanet science. The combination of CODEX with a high-contrast imager on the E-ELT is of particular interest because of its wide range of important applications. An imager equipped with an extreme AO system and a coronagraphic device (e.g. EPICS⁴) will be capable of directly detecting at least some of the more massive planets discovered by CODEX using the radial velocity method, as well as other planets in the same systems. The combination of these instruments will be able to provide the E-ELT community with a full characterization of the planet's orbits as well as with basic knowledge on atmospheres, true masses and temperature.

CODEX will also be needed to obtain crucial radial-velocity follow-up observations of transiting exoplanet candidates discovered by various space missions. For example, the planned PLATO satellite will be capable of detecting the transits of Earth-sized planets in the habitable zone of nearby solar-type stars. However, to confirm the planetary origin of the detected photometric signal and to precisely measure the mass of the transiting body in these cases will require a radial velocity precision of better than 10 cm/sec, which only CODEX will be able to provide.

Another important synergy is that between CODEX and GAIA. Together these instruments will be able to probe stellar evolution theory by comparing physical stellar parameters derived by GAIA from accurate positions on the H-R diagram in combination with theoretical stellar evolutionary tracks with those derived by CODEX from (i) measurements of the radioactive element Th and (ii) from asteroseismology of metal-poor stars. Several future facilities such as LSST, JDEM and EUCLID will seek to constrain the properties of Dark Energy, mostly using surveys of SNIa, weak lensing, and galaxy clustering. However, a redshift drift measurement by CODEX would probe the expansion rate in a redshift range that will remain largely inaccessible to most other methods even in the ELT era (the only exception being SNIa surveys). CODEX measurements of the redshift drift at $z = 2 - 4$ would therefore provide an important complement to the constraints on the expansion rate at $z < 2$ obtained by other techniques. Finally, CODEX will also work in synergy with ALMA and SKA to constrain the possible variability of physical “constants”. High-redshift molecular rotational absorption lines discovered by ALMA and HI 21cm absorption detected by SKA can be compared to optical metal lines observed with CODEX to constrain various combinations of constants involving the fine structure constant (α), the proton-to-electron mass ratio (μ) and the proton g-factor. In addition, SKA may be able to detect “conjugate” satellite lines of OH which by themselves will constrain a particular combination of α and μ .

2. THE CODEX DESIGN

The overall instrument scheme is sketched in Figure 4. The thick lines represent the photon flux. Science photons are represented in green while guiding photons are represented in orange. Calibration photons are in pink. The area highlighted in light blue is optional and describes the possibility to implement a Wave-Front sensor to feed back information to M4/M5 for PSF shape improvement or a complete closed loop WFS Deformable Mirror with the same purpose.

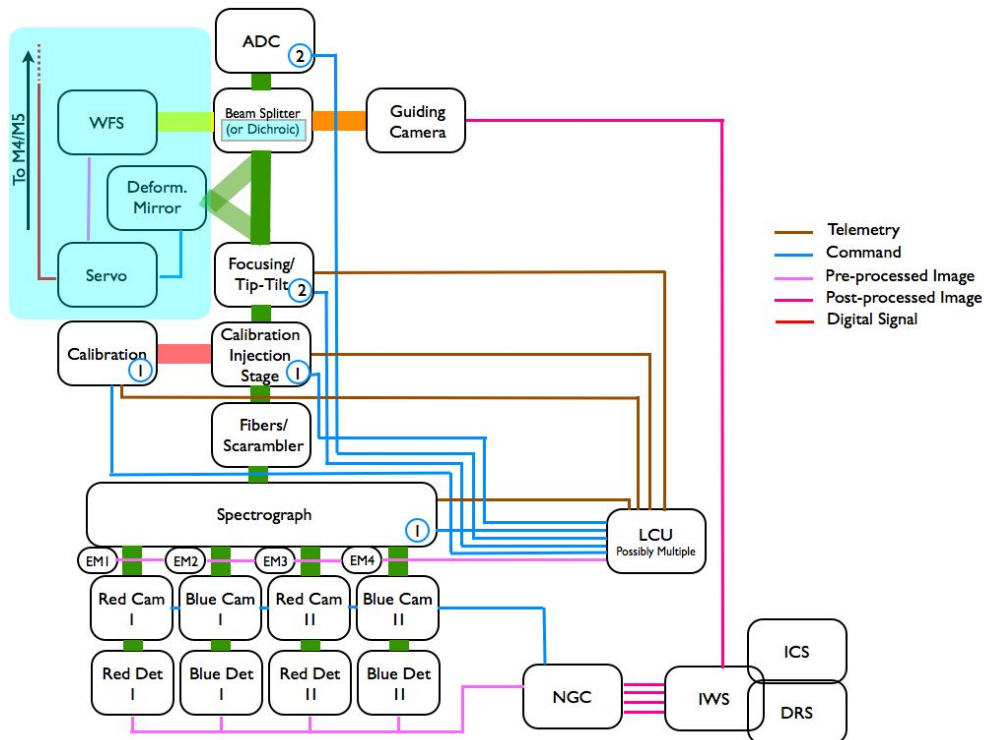


Figure 4. Schematic outline of the CODEX instrument. The blue box on the upper left indicates the WFS system, to compensate for possible degradation of image quality. This system is not part of the baseline, but provision has been made to insert it in the following phases, if deemed necessary.

The top-level technical specifications have been derived from the requirements set by the main science. The challenge is to provide a seeing-limited spectrograph that combines high resolving power, high precision and high efficiency for a 42 m telescope with reasonable resources.

2.1 The laser frequency comb: an absolute and reproducible calibration standard into astrophysical spectroscopy

One of the most crucial subsystems of CODEX will be its wavelength calibration source. The spectrum of an ideal calibration source has a high density of unblended, regularly spaced lines of uniform intensity covering the entire spectral range of interest. The wavelengths of these lines should be known from first principles and they should remain stable and reproducible to high accuracy for many years.

Traditional methods of wavelength calibration (e.g. the use of Th-Ar comparison spectra) are not able to meet the high demands of CODEX on accuracy and stability. Instead, the best approximation of an ideal wavelength calibration source currently known, and hence the most promising device for CODEX, is a so-called laser frequency comb (LFC). The core of a LFC is a mode-locked laser emitting a repetitive train of femtosecond pulses. In frequency space this results in thousands of equally spaced modes covering a bandwidth of several THz. The mode spacing is given by the pulse repetition frequency, which resides in the radio frequency domain. The repetition frequency can readily be synchronized with a precise radio frequency reference such as an atomic clock. These clocks provide by far the most precise measurements of time and frequency currently available, which are in turn the most reliably determined quantities in physics. The novelty of the LFC and its tremendous benefit for many areas of physics has been widely recognized with the award of the 2005 Nobel Prize in Physics to T.W. Hänsch and J. Hall for fundamental and pioneering work in the development of the optical frequency comb technique.

An LFC offers a number of advantages over traditional wavelength calibration sources. (i) the absolute position of each line is known a priori (i.e. without reference to any laboratory measurements) with relative precision better than 10⁻¹², which is limited only by the radio frequency clock; (ii) the density of lines may be as high as permitted by the spectrograph's resolution while at the same time guaranteeing the absence of blended lines; and (iii) the line density is perfectly uniform⁵.

The development and testing of a prototype Laser Frequency Comb system for HARPS in collaboration with the Max Planck Institute of Quantum Optics is at an advanced stage^{6,7,8}. These efforts have proceeded extremely well. We are thus confident that wavelength calibration with an LFC is set to become the new standard in high-precision spectroscopy. With an LFC with pulse repetition rate in the range 5–30 GHz (so that the lines are resolved from each other by CODEX), and of a uniform intensity of all comb modes over the full CODEX wavelength range, a photon-noise limited wavelength calibration accuracy < 1 cm/sec for every single exposure can easily be achieved by CODEX. The built-in stability and reproducibility of the LFC spectra ensure that any evolution in the distortions of the wavelength scale induced by the spectrograph or detector may be accurately tracked over essentially arbitrary timescales.

2.2 The CODEX optical design

Based on our substantial experience in echelle spectroscopy we have developed a spectrograph concept with a number of novel design aspects which make CODEX a very compact and contained instrument⁹. Given the high precision aimed by the project, the spectrograph has been located in the coudé focus that is the quietest (mechanically and thermally) environment available.

The instrument plus telescope has to be seen as a unit in order to assess the final performance. The coudé train has therefore also been designed and analyzed. In order to avoid image motions induced by the unavoidable turbulence in the coudé ducts, the design proposes to seal the coudé path slightly above the thermally controlled coudé room.

The light is collected at the coudé focus by a fibre interface which leads into a guiding and tip-tilt correcting system (see Figure 5) that accurately centres the object light into the 500 µm fibre core. This optical system also contains the instrument ADC and the interface to the calibration system. The light is guided by fibres into the spectrograph vessel. In the fibres the light is scrambled in order to make the output signal independent of variations at the entrance. There are no active elements in the spectrograph vessel.

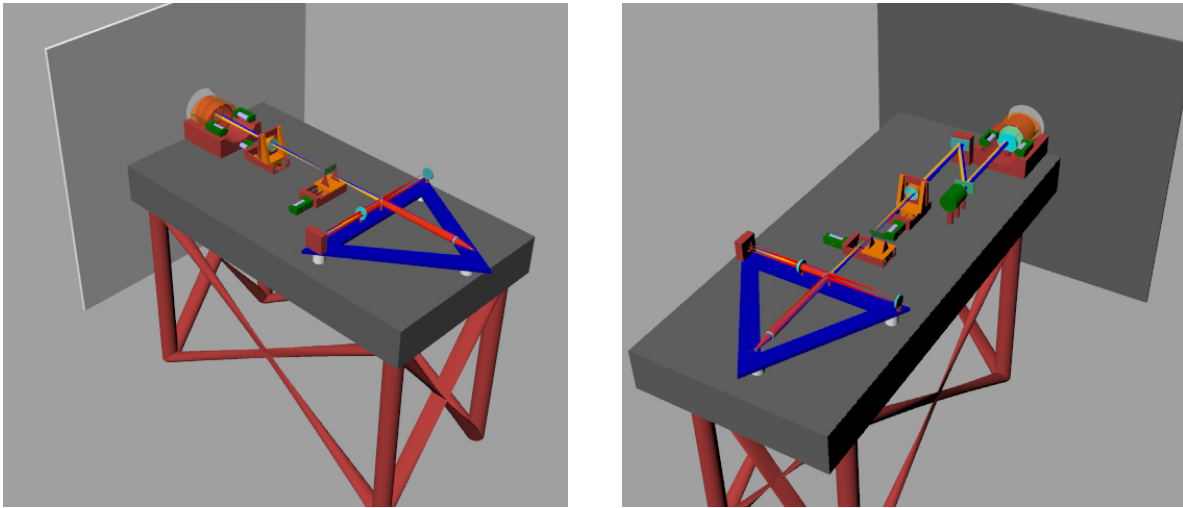


Figure 5. E-ELT coude design Light Injection scheme of CODEX: baseline tip-tilt solution (left panel) and optional WFS-DM solution (right panel).

In the spectrograph the pupil is made highly anamorphic and sliced in 6 parts, which pass through the 1.7 m long echelle and the collimating system of the spectrograph, after which they are divided into two separate paths (Blue and Red). Each path is imaged onto two separate cameras, each equipped with 9cm x 9cm monolithic detectors. The preferred pixel size is of 10 μm , but large pixels can be accommodated. Detectors of this size have been produced already. Figure 6 shows the optical layout, and Figure 7 the optomechanical concept. Thanks to its crossdispersed format, the whole range 380-719 nm will be covered simultaneously with 60 echelle orders. Two fibres will be used, one for the object and one for sky or simultaneous calibration, separated by 30 pixels, which is also the minimum separation between adjacent orders.

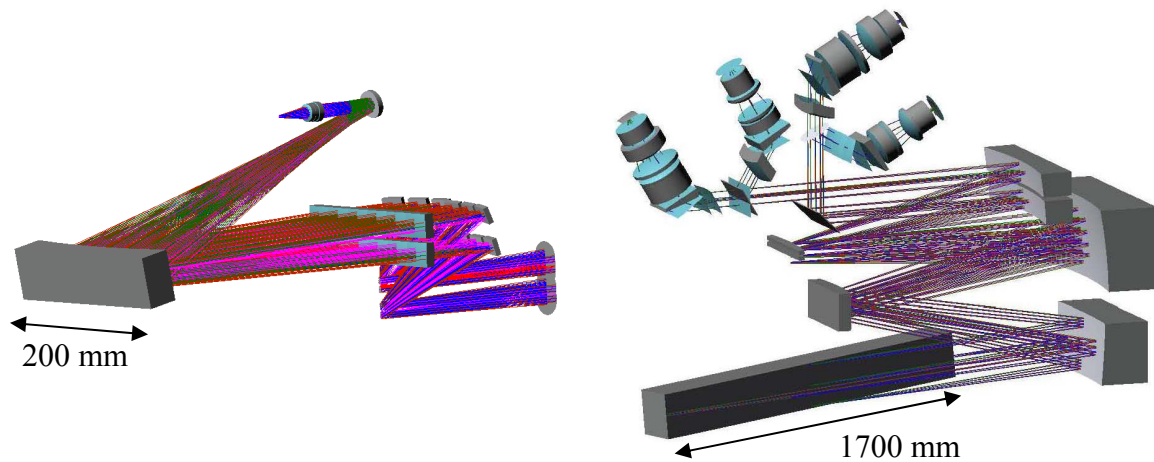


Figure 6. Optical layout of the anamorphic pupil slicer (left) and spectrograph (right) of CODEX. Note that the two figures are not to the same scale.

2.3 Thermo – Mechanical Concept

The mechanical concept builds on the HARPS experience and aims to obtain the highest mechanical and thermal stability and to minimize the effects to be corrected for with a spectrograph in a mild vacuum. The thermal environment is designed to be progressively more stable with 10 mK variations within the spectrograph and 1 mK variations at the CCD. No movable parts are allowed in the spectrograph vessel. Special care is taken with the design of the detector head to keep it very stable, both thermally and mechanically, for instance by ensuring a continuous flow of nitrogen to cool the CCD.

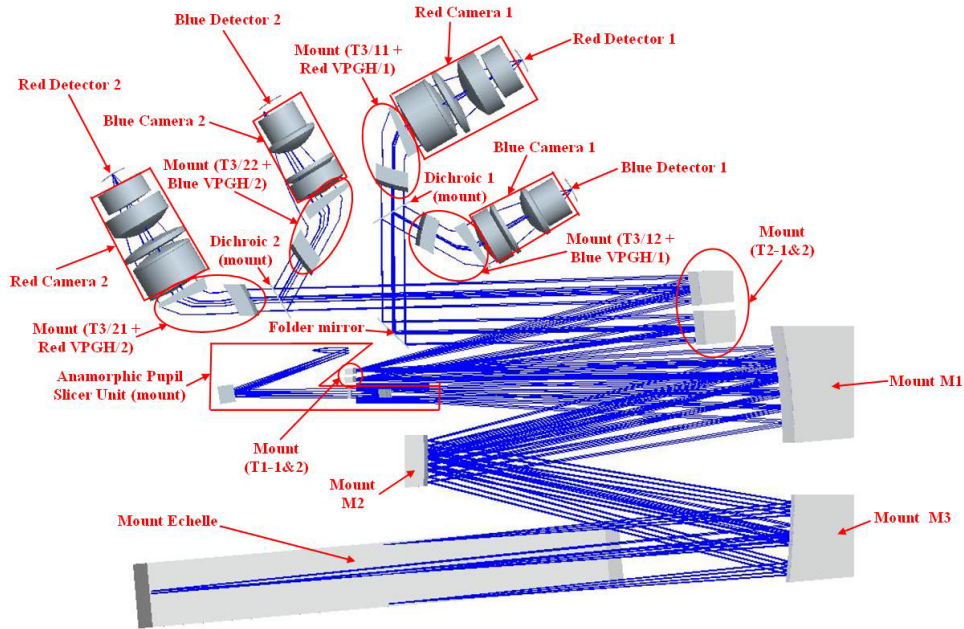


Figure 7. Opto-mechanical design of CODEX

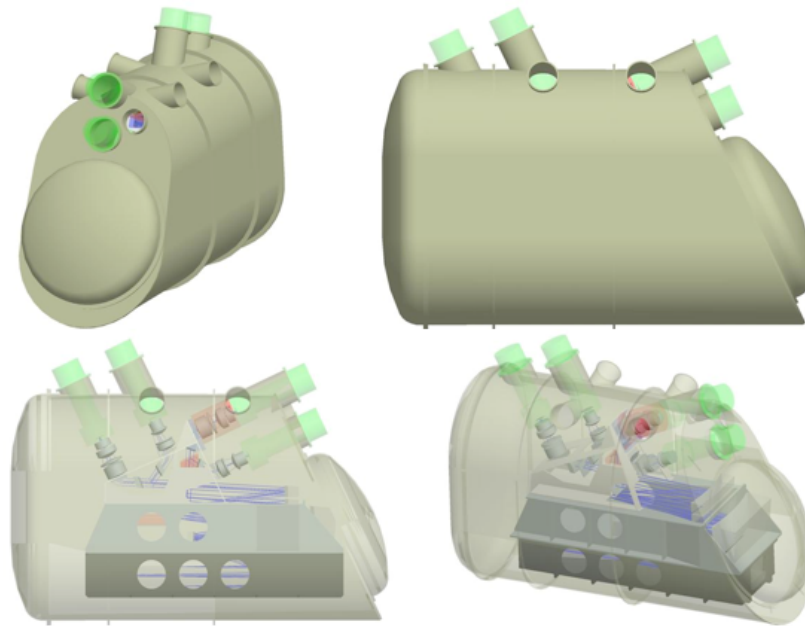


Figure 8. Design of the Vacuum Vessel of CODEX: the size is 4(l) x 1.5(w) x 3(h) m.

The optical system is mounted on three optical benches. Special care is taken with the selection and processing of materials. The materials are the same everywhere to avoid differential thermal expansion. Figure 8 shows a picture of the spectrograph vessel. The dimensions of the whole spectrograph including the vacuum vessel are less than 4(l) x 1.5(w) x 3(h) meters. Figure 9 shows the spectrograph room within the coudé lab. The different rooms provide progressively higher levels of temperature stability.

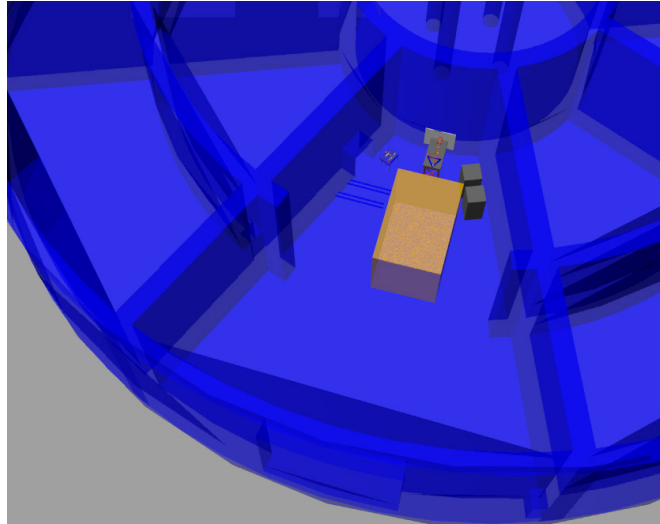


Figure 9. CODEX in the coudé laboratory at the E-ELT.

2.4 Control SW and Electronics

CODEX should be seen as a distributed system composed of several collaborating/communicating sub-systems. The software architecture is based on the VLT software model with high-level software (OS) responsible for receiving input (from users, templates etc.), for handling exposure cycles and for coordinating the activities of all other involved lower-level software packages (CODEX low-level part – ICS, DCS, TCS and Archive). In the case of the VLT all these software systems are implemented as stand-alone processes. Our approach follows what is called the component container paradigm. The system is modeled as a set of collaborating components located inside one or more containers. Adopting this design philosophy, the initial design of the CODEX control software, is based on the ACS framework. It is assumed that there will be a similar software framework for the E-ELT as exists for the VLT which will deliver all the typical services of a modern control system (e.g. error reporting, alarm as well as logging, handling and communication infrastructure etc.). If a different framework should be adopted, the CODEX software architecture will be adapted accordingly. The design of the electronic architecture is also based on a fully modular approach. The sub-systems of CODEX will be controlled by different nodes, usually composed of a CPU and several I/O specific modules with decentralized I/O. The nodes can thereby be located separated from the CPU and will communicate with it by means of an “industrial bus”, usually based on a physical Ethernet layer. The main building blocks of the proposed electronic design are programmable logic controllers (PLC), field busses, decentralized I/O modules and motion controllers.

No particularly demanding requirements have been identified for the Control software and Electronics. The only critical aspect is the long lifetime expected for the instrument, which will require an accurate maintenance plan.

2.5 Data Reduction and Analysis

We have performed an end-to end concept study. A full scientific pipeline and a very competitive set of analysis tools allowing to achieve the main science goals of CODEX will be part of the set of deliverables.

3. CODEX PERFORMANCE

The greatest advance of CODEX with respect to current spectrographs stems from the combination of photon collecting capability, high resolving power and unique Doppler precision.

When judging the challenge to be met by CODEX it is important to realize that a precision of 2 cm/sec corresponds to a shift of only 3.2 Angstroms in the detector plane. This is the scale of shifts we aim to detect. A theoretical calculation of a full error budget is beyond the scope of the present study. We have instead scaled our experience with HARPS and with our prototypes to obtain reasonable estimates of the CODEX performance.

The Top Level Requirements have been broken down into subsystem requirements and we have traced Doppler precision and system transmission through the whole chain.

3.1 Instrumental sources of RV errors

Simultaneous control of the shifts on the detector with an adequate calibration unit is the key aspect of the spectrograph design. There are only three errors, which cannot be eliminated by the simultaneous calibration correction and must be controlled separately. All three of them have been extensively addressed in our R&D program.

- **Stability of the reference source:** any instability of the reference source will directly translate into measurement errors. The commonly used Th-Ar lamps are not sufficiently stable for the required precision. A novel LFC calibration system is therefore being developed.
- **Stability of image and pupil:** while the calibration light can be made very homogeneous and stable, this is not the case of the astronomical light. A combination of accurate centring and scrambling is required. R&D on fibres and a tip-tilt input system has been carried out.
- **Differential motions of the detector:** photons from the simultaneous calibration and from the astronomical objects are not detected by the same CCD pixels. Differential motions between pixels in the detector can produce RV errors. By testing the HARPS detectors we have shown that a reasonable thermal control of the cryostat reduces this effect to insignificant levels.

The instrumental error budget has been divided as detailed in the following table:

Item	Percent	Projected on Sky [mas]		Size at coudè plane [µm]		v [cms-1] (Å on detector)
		G=1500	G=3500	G=1500	G=3500	
Detector Stability	10%	0.98	2.30	10.26	23.59	0.20 (0.32)
Calib. Line Stability	10%	0.98	2.30	10.26	23.59	0.20 (0.32)
PSF Centroid Stability	60%	5.90	13.80	61.56	141.59	1.20 (1.92)
System Maturity Margin	20%	1.97	4.60	20.59	47.18	0.40 (0.64)
Total	100%	9.84	34.4	100.96	235.98	2.00 (3.20)

Table 1. Breakdown of the Radial Velocity Error Budget (in Angstroms and cm/sec on the detector) for different scrambling capabilities. Our tests indicate that all subsystem can fulfil the specifications. Two values of fibre scrambling gain G (1500 and 3500) are considered. Microns and Angstroms in the table are in physical units.

3.2 Astronomical sources of RV errors

In addition to the instrumental effects considered in the previous section, some astronomical sources of noise may contribute to the error budget for the most accurate Doppler measurements. The most important of these are as follows.

- **Earth orbital velocity, Earth rotation:** residual errors should be less than 0.5 cm/sec.
- **Target Coordinates:** a 70mas error corresponds to a 1 cm/sec Doppler uncertainty; object coordinates must be known better than to a few tens of mas.
- **Timing:** a 0.6 sec error corresponds to a 1 cm/sec Doppler uncertainty; the flux weighted mid-time of the observations must be known to better than a fraction of second. The exosumer is built to make this error insignificant.
- **Sky and nearby objects contamination:** For continuum sources (sky emission lines will be masked in post-processing) our simulations show that $\Delta M \sim 2.5$ between object magnitude and sky brightness is sufficient, even for the most demanding case.

3.3 Summary of Characteristics & Performances

Taking into consideration the transmission efficiency of all optical components (including the E-ELT mirrors and 20% slit losses) and the detector efficiency, the total expected system transmission is ~20%. This is more than 2 times better than the total system transmission of HARPS and comparable to the transmission of the most efficient H-R spectrographs (which are located at more efficient focus).

Aperture on the sky	0.82 arcsec, with a \varnothing 500 μ m fibre at F/3; 80% of flux are collected assuming the model E-ELT PSF of 0.65" square fibres
Feeding	2 fibres, one for object, one for sky or simultaneous calibration
Wavelength range	370-710 nm, split in two arms by dichroics BLUE: 370-500 nm; RED: 490-710 nm
Doppler Precision	< 2 cm/sec over 30 years
Wavelength Precision	< 1 m/sec (absolute wave length calibration of each spectral pixel)
Resolving Power	120000 for square fibre, ~ 135000 for circular fibre
Sampling	4 pixel/spectral element
Spectral format	cross-dispersed echelle
Echelle	R4, 41.6 l/mm, 1700x200 mm, 4x1 mosaic
Order separation	>30 pixels (>300 μ m) between adjacent orders 30 pixels (300 μ m) between object and sky fibre
Order height	0.705 mm x 2 (141 pixels of 10 μ m size)
Camera focal ratio	F/1.5 (on-axis)
Detector focal plane	Four CCDs (2 in Blue Camera, 2 in Red Camera), each with 9 x 9 K 10 μ m pixels
Total efficiency	28.8% (maximum), 13.5% (minimum) from telescope to detector focal plane, slit losses are not included
Auxiliary functions	Own Calibration Unit including LFC, Exposure meter system, CCD flatfield, LEDs for maintenance, Centering and Autoguiding system

Table 2. Summary of CODEX characteristics

We stress that such a high efficiency can only be obtained if special coatings can be applied on large surfaces.

REFERENCES

- [1] Liske, J., Grazian, A., Vanzella, E., Dessauges, M., Viel, M., Pasquini, L., Haehnelt, M., Cristiani, S., Pepe, F., Avila, G., Bonifacio, P., Bouchy, F., Dekker, H., Delabre, B., D'Odorico, S., D'Odorico, V., Levshakov, S., Lovis, C., Mayor, M., Molaro, P., Moscardini, L., Murphy, M. T., Queloz, D., Shaver, P., Udry, S., Wiklind, T., Zucker, S., "Cosmic dynamics in the era of Extremely Large Telescopes", *MNRAS* 386, 1192-1218 (2008)
- [2] Mayor, M., et al., "Setting New Standards with HARPS", *The Messenger* 114, 20-24 (2003).
- [3] Pepe, F., Cristiani, S., Rebolo Lopez, R., Santos, N. C., Amorim, A., Avila, G., Benz, W., Bonifacio, P., Cabral, A. P., Carvas, P., Cirami, R., Coelho, J. M. P., Comari, M., Coretti, I., Delabre, B., Di Marcantonio, P., D'Odorico, V., Fleury, M., García López, R. J., Herreros, J.-M., Hughes, I., Iwert, O., Lima, J., Lizon, J.-L., et al., "ESPRESSO: the Echelle spectrograph for rocky exoplanets and stable spectroscopic observations", *Proc SPIE* 7735-14, in preparation
- [4] Kasper, M. E., Beuzit, J.-L., Verninaud, C., Baudoz, P., Boccaletti, A., Gratton, R. G., Bonavita, M., Keller, C. U., Kerber, F., Schmid, H. M., Thatte, N. A., Tecza, M., Venema, L. B., Jager, R., Yaitskova, M., Allercarpentier, E., Martinez, P., Hubin, N., "EPICS: direct imaging of exoplanets with the E-ELT", *Proc. SPIE* 7735-84, in preparation
- [5] Murphy, M. T.; Udem, Th.; Holzwarth, R.; Sizmann, A.; Pasquini, L.; Araujo-Hauck, C.; Dekker, H.; D'Odorico, S.; Fischer, M.; Hänsch, T. W.; Manescau, A., "High-precision wavelength calibration of astronomical spectrographs with laser frequency combs", *MNRAS* 380, 839-847 (2007).
- [6] Steinmetz, T.; Wilken, T.; Araujo-Hauck, C.; Holzwarth, R.; Hänsch, T. W.; Pasquini, L.; Manescau, A.; D'Odorico, S.; Murphy, M. T.; Kentischer, T.; Schmidt, W.; Udem, Th., "Laser Frequency Combs for Astronomical Observations", *Science* 321, 1335-1337 (2008).
- [7] Wilken, T., Lovis, C., Manescau, A., Steinmetz, T., Pasquini, L., Lo Curto, G., Hänsch, T. W., Holzwarth, R., Udem, Th., "High-precision calibration of spectrographs", *MNRAS* 405, L16-L20 (2010).
- [8] Wilken, T., Lovis, C., Manescau, A., Steinmetz, T., Pasquini, L., Lo Curto, G., Holzwarth, R., Hänsch, T. W., Udem, Th., "High-precision calibration of spectrographs using laser frequency combs", *Proc. SPIE* 7735-29, in preparation
- [9] Delabre, B., Manescau, A., "CODEX optics", *Proc. SPIE* 7735-205, in preparation