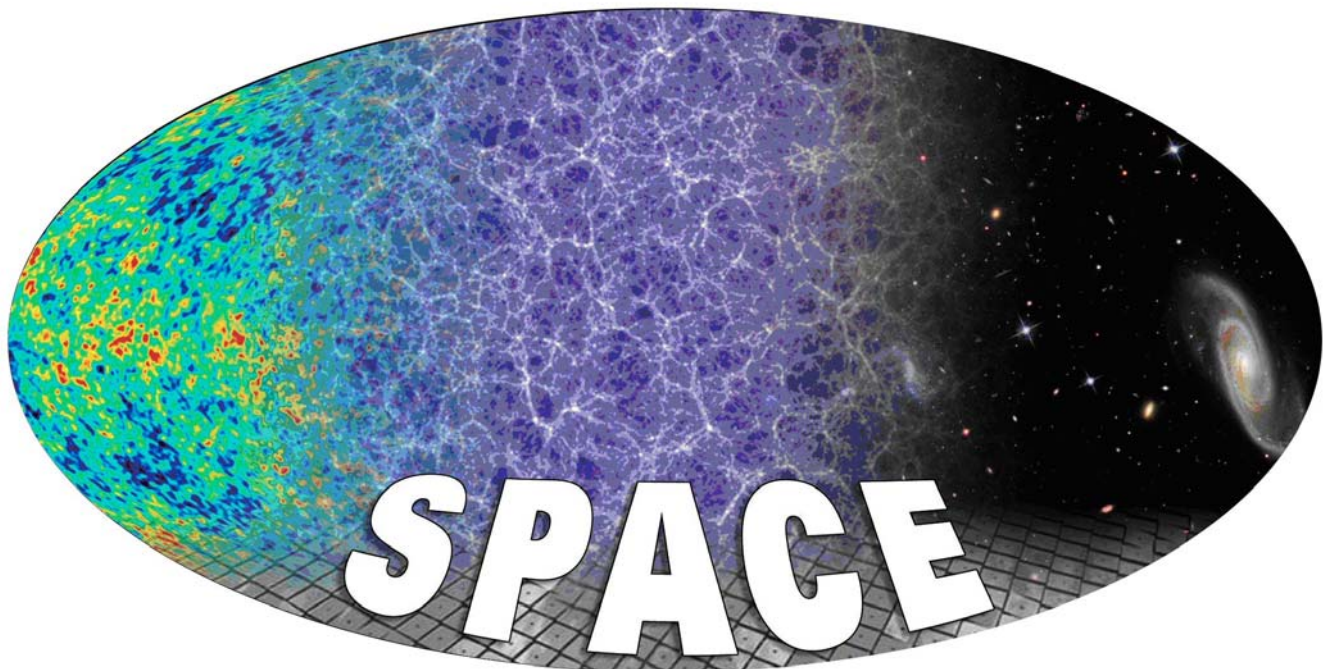


SPACE

(Spectroscopic All-sky Cosmic Explorer)

Building the 3-d Map of the Accelerating Universe

A response to a Request for Information for the NRC ASTRO-2010 Survey



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Executive Summary

Imagine building the 3-dimensional map of the Universe. Imagine measuring with high precision the distances of five hundred million galaxies regardless of their spectroscopic features, detecting with ultimate accuracy baryonic acoustic oscillations and the growth rate of structures free from selection biases. Imagine obtaining the main physical parameters of each galaxy, building the most remarkable dataset of astrophysical data ever assembled. Can we do it today? Can we do it at the cost of a medium-class mission? Can we launch and get the results within this decade? Could this be one of the great legacies left by the Astro2010 Decadal Survey?

The answer is yes. Exploiting the enormous advances in nano-technology, we have envisioned a space mission capable of producing the three-dimensional evolutionary map of the Universe over the past 10 billion years. The SPectroscopic All-sky Cosmic Explorer (*SPACE*) takes near-IR spectra of $\sim 0.5 \times 10^9$ galaxies down to $AB \sim 23$ over the 3π sr of sky unobscured by the Galaxy. This allows *SPACE* to precisely locate ($\Delta z \sim 0.001$) each galaxy, measuring baryonic acoustic oscillation (BAO) and the evolution of structure formation during the matter and dark energy dominated eras. *SPACE* improves the figure of merit for knowledge of dark energy by more than an order of magnitude and fully discriminates between theories of dark energy and theories of modified gravity. The colossal spectroscopic catalogue of half billion galaxies out to $z \sim 2$ enables a new class of investigations into the formation, evolution, and interaction of galaxies in the Universe, providing a legacy to be data mined for decades.

SPACE achieves its remarkable sensitivity, sky coverage, and sampling frequency by performing multi-slit near-IR spectroscopy in outer space, fully exploiting the sky background ~ 500 times lower than from the Earth. For dark energy studies, the spectroscopic approach is immune to the intrinsic systematic of other methods. Working in slit-mode, *SPACE* has also enormous advantages over slitless spectroscopy. After completion of the all-sky survey, *SPACE* maintains unlimited potential as an extended mission with GO programs on virtually every General Astrophysics theme. In particular, a deep survey over a smaller area would not only enable to discover a huge number of primordial galaxies at very high redshift, but also to search and measure with extremely high efficiency cosmological Type Ia SNe. As the ideal complement to LSST, *SPACE* enables weak lensing science as an important complement to BAO and SNe. The major X-ray and radio projects currently under study would also greatly benefit from a deep all-sky spectroscopic mission.

SPACE, originally conceived as a joint ESA-NASA project, has won the ESA selection (medium-class) for the Cosmic Vision 2015-2025 planning cycle. ESA has then merged a less capable version of *SPACE*, called *ENIS*, into the *EUCLID* mission, and a further merging of *EUCLID* into *JDEM (IDECS)* is now being considered. We believe that ***SPACE*, as originally proposed, has by far the most exciting capabilities, with a scientific potential so broad and compelling that exceeds even the investigation of dark energy.** In this uncertain scenario, NASA has a unique opportunity of taking a leadership role promoting this wonderful mission. **Either as a key component of *JDEM/IDECS* or as a standalone mission,** *SPACE* represents a historic opportunity in our quest for understanding the Universe.

I. Science Case for *SPACE*

Our view of the Universe has changed dramatically over the past two decades through measurements of the cosmic microwave background anisotropy, the large-scale structure of the local Universe ($z < 0.3$) and the brightness of high-redshift supernovae. Fully 96% of the Universe consists of dark energy (73%) and dark matter (23%), which govern the expansion history and evolution of cosmic structures, leaving their imprints on the structure and distribution of visible galaxies. They are unexplained in standard physical theory. The resolution of this mystery through new particles or modification to the theories of gravity, quantum mechanics or the standard model, is the most important problem in physics. The need to address it has been underlined by the most prominent scientific advisory committees.

The existence of dark energy and dark matter explains an enormous range of observations assuming only that dark energy produces a pressure countering gravity and dark matter behaves like ordinary matter in its effect on space-time. This standard paradigm not only makes testable predictions about how the dark components affect the rate of expansion of the Universe, but can predict how cosmological visible structures develop through gravitational instability driven by dark matter. These predictions can be discriminated by studying several classes of astrophysical phenomena, in particular Type Ia Supernovae (SNe Ia), Weak Lensing (WL), Baryonic Acoustic Oscillations (BAOs), Redshift-Space Distortions, Cluster Counts and the Alcock-Paczynski Test. A number of scientific white papers submitted to Astro2010 discuss these techniques and strongly support major investments in advancing our understanding of dark energy. In particular, Riess et al. (2009) made the case for exploring dark energy from a space-based platform, the Joint Dark Energy Mission (*JDEM*).

The combined quest for ultimate sensitivity (to study the evolution of dark energy with time), high optical stability (for photometric and geometric accuracy) and wide field coverage (to beat down cosmic variance) naturally calls for a space-based approach. NASA and DOE are jointly developing *JDEM*, a space mission that will utilize all three main techniques for probing dark energy: BAO, weak lensing, and SNe. ESA is developing *EUCLID*, a dark energy space mission concept that has evolved from two complementary mission concepts, *DUNE* and *SPACE*.

Among these missions, *SPACE* represents the most original and exciting project: a 1.5m telescope with a 0.4 deg² FOV, which can take spectra of up to 6000 objects simultaneously with DMDs as slit selection mechanisms. Observing at $R \sim 400$ from 0.8 to 1.8 microns, *SPACE* perform an “all-sky” survey down to $H_{AB} \sim 23$ and reconstructs the 3-d structure of the Universe by measuring with high precision and without selection biases the redshift of about 500 million galaxies over the last 10 Gyr of time. This allows to directly producing two independent measures of cosmic evolution (**BAOs and the growth rate of cosmic structures**) capable of breaking the degeneracy between different theories of cosmic acceleration. Unlike other proposed dark energy missions, *SPACE* also has a **unique legacy value** for the study of individual galaxies and our understanding of galaxy evolution. In fact, dark energy is one of the key questions that the *SPACE* survey can address, but not the only one. *SPACE* can also perform a variety of tests on the Big Bang, inflation, the growth and evolution of the cosmic web and the matter content of the Universe, giving it broad impact on our understanding of cosmology. In the following sections, organized as a function of cosmic time, we provide a brief selection of the key questions *SPACE* can attack.

1.1 Density fluctuations from inflationary big bang theory and the cold dark matter model

The pattern of transient quantum fluctuations in the density of the Universe frozen and boosted to large scales during inflation should have left a measurable feature in the power spectrum of the matter distribution, corresponding to a **turnover or maximum around a spatial wavenumber of $k \sim 0.01 h/\text{Mpc}$** .

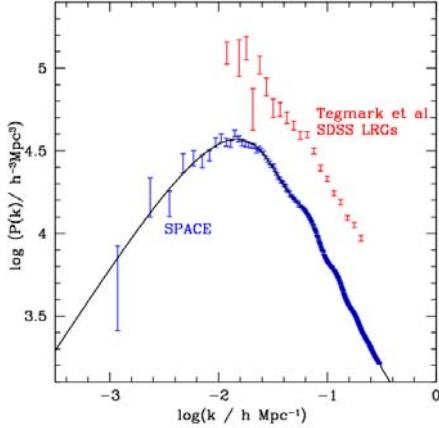


Figure 1. The power spectrum of density fluctuations. The solid line shows the prediction of the concordance cold dark matter model. The maximum power is at the scale corresponding to the size of the horizon at the epoch of matter-radiation equality. The red symbols show the current best measurement of the power spectrum from SDSS LRGs (Tegmark et al. 2006). The blue symbols show the forecast for the power spectrum which will be measured by SPACE. The width of the $P(k)$ turnover constrains the relative amounts of cold dark matter, massive neutrinos and baryons.

The huge volume covered by *SPACE* (Figure 1) allows us to measure the power spectrum at spatial frequencies more than an order of magnitude smaller than the location of the turnover. The position and shape of the turnover in the power spectrum provides a precision measurement of the matter density of the Universe, along with the fraction of this mass in the form of cold dark matter, massive neutrinos and baryons. This measurement would be the first direct probe of primordial density fluctuations, which have only been measured to date via temperature ripples in the CMB. The slope of the power spectrum on these large scales can distinguish between different models of inflation, which generally predict a power law exponent, n , close to but not precisely equal to 1.

1.2 Baryonic Acoustic Oscillations

Baryonic acoustic oscillations (BAO) are small amplitude (5-10%) modulations in the distribution of matter imprinted at the epoch when matter and radiation decoupled ($z \sim 1000$). The length scale of the oscillations ($\sim 150\text{Mpc}$) is accurately known from measurements of CMB temperature fluctuations. This physical scale will have different apparent sizes on the sky at different redshifts and in different cosmologies. Assuming that the distribution of galaxies reflects the distribution of all matter, this physical scale is measured from the spatial correlation (i.e. the power spectrum) of galaxies.

The acoustic oscillation length can be measured in the transverse and the radial directions (3D) from the distribution of galaxies. Combining the apparent size with the known physical size gives the distance at the redshift of observation and makes it possible to determine the expansion rate as a function of redshift, $H(z)$. The astrophysical effects which may cause deviations of the ideal BAO signature are now well understood from numerical calculations. Angulo et al (2007) demonstrated that the primary limitation on the accuracy of the BAO method is sample variance. Thus, to minimize the uncertainty in the dark energy equation of state $w(z)$, the observations need simply to maximize the survey volume.

SPACE measures galaxies over $\frac{3}{4}$ of the entire sky and over the redshift interval $0 < z < 2.5$, centred on the redshift $z \sim 1$ at which the dark energy first starts to dominate the expansion of

the Universe. The sensitivity requirement is $\text{SNR} \sim 5$ per resolution element at $H_{\text{AB}} \sim 23$. A space-based multi-object IR spectrometer makes it possible to get accurate redshift of millions of galaxies over the whole sky in a short time. *SPACE* sensitivity allows measuring both emission-lines and absorption features, providing independent BAO measures for multiple classes of galaxies characterized by different bias. This allows for **an internal check against scale-dependent bias, a major systematic of the BAO method.**

The evolution of the dark energy will be measured by dividing the sample into redshift slices of width $\Delta z \sim 0.4$ each and measuring the BAO signature in each slice. *SPACE* achieves **0.2% accuracy** in the BAO scale measurement from these redshift slices, far superior to that expected from any other survey, as illustrated by Figure 2.

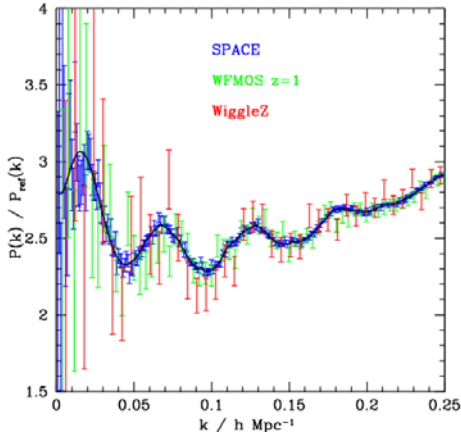


Figure 2 - The appearance of BAO in selected ongoing and future surveys. The measured power spectrum has been divided by a featureless reference spectrum to show the BAO more clearly. WiggleZ is an on-going survey of emission line selected galaxies at $z \approx 0.7$. WFMOS is a spectroscopic, ground-based survey proposed for Subaru. The blue points show the measurements expected from the full survey volume of *SPACE*. The black solid line represents the theoretical model for the BAO. The high frequency sampling and small errors of $P(k)$ from *SPACE* mean that we will achieve the definitive measurement of the BAO. The statistical power of the *SPACE* BAO measurement is around an order of magnitude better than that expected from WFMOS.

The multi-slit approach of *SPACE* provides an order of magnitude gain over the most ambitious ground-based survey proposed and a factor of several improvement over any competing space mission. ***SPACE* sets the standard for dark energy constraints from BAO** and is not likely to be superseded for decades. Using the Dark Energy Task Force (DETF) Figure of Merit $\text{FoM} = [\det \text{Cov}(w_0, w_a)]^{-1/2}$, where $\text{Cov}(w_0, w_a)$ is the covariance matrix of (w_0, w_a) , $\text{FoM} = 1/(\Delta w_0 \Delta w_a)$ (<http://home.fnal.gov/~rocky/DETF/>), a combination of *SPACE* BAO measurement with a “long-term” Stage IV experiment (LSST, *JDEM*, SKA) produces a further factor of three gain in the constraints on dark energy (Figure 3), i.e. ***SPACE* falls in the next category of Stage V experiments!**

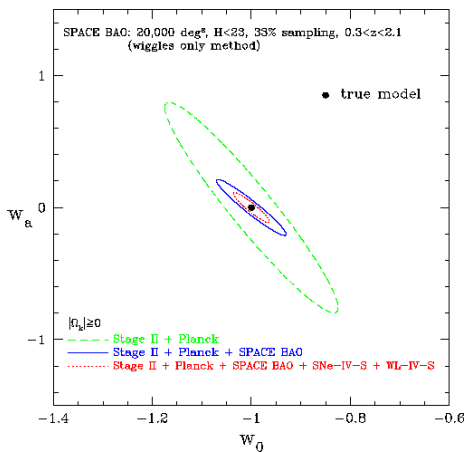


Figure 3: The expected constraints on dark energy parameters (w_0, w_a) , from *SPACE*, assuming a 20,000 square degrees survey (*EUCLID* baseline). *SPACE* is designed to reach DETF Stage IV FoM using only the most conservative measurements of the BAO (“wiggles only” approach, see Seo & Eisenstein (2007)), and pessimistic assumptions about SN Ia systematic errors (see Albrecht et al. (2006)). For reference, we provide the estimated FoM (-S stands for space project):

Projects	DETF FoM
Stage II + Planck:	53.3
<i>SPACE</i> BAO + Stage II + Planck	527.1
<i>SPACE</i> BAO + Stage II + Planck + WL IV-S + SNeIV-S	1567.2

1.3 The Growth Rate of Cosmic Structures

The growth history of cosmic large scale structure $f_g(z)$ can be probed through independent measurements of gravitationally induced galaxy redshift-space distortions and the bias factor between the distribution of galaxies and that of matter; this enables us to differentiate between an unknown energy component and modified gravity as possible causes for the observed cosmic acceleration (Guzzo et al. 2008; Wang 2008).

SPACE will make a dramatic improvement, thanks to enormous volume sampled, even in slices of $\Delta z=0.2$, and to the deep infrared selection ($H<23$), that allows the $N(z)$ to extend significantly above $z=1.5$, with a mean density always larger than ~ 0.02 gal h^3 Mpc $^{-3}$ to $z\sim 2$ even with a sampling of 1/3 galaxies. Our simulations clearly show that ***SPACE* will be unique in providing a precision measurement of the growth history of cosmic structures**, reaching 0.5% accuracy in the redshift-space distortion parameter β in redshift slices of $\Delta z=0.2$, and measuring directly the growth function $f_g(z)$ to 1% accuracy (Figure 4). The bias factor (b) will be extracted in each redshift slice using higher-order galaxy clustering (Verde et al. 2001) or via self-consistent density-reconstruction methods (e.g. Sigad et al. 2000).

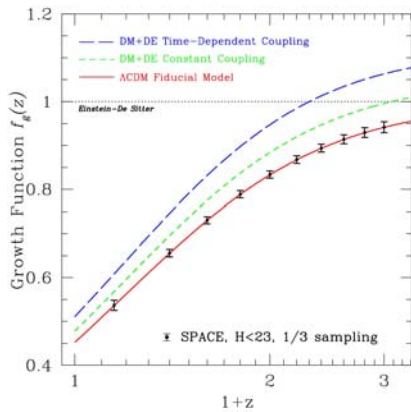


Figure 4. The predicted performance of *SPACE* in measuring the growth rate of density fluctuations as a function of redshift, $f_g(z)$ using the anisotropy of galaxy correlations, assuming a Λ CDM fiducial model. *SPACE* will disentangle to high accuracy the cosmological constant theory from variants of dark energy (here two possible cases are shown - Amendola 2000). The combination of the fully independent measurements of $H(z)$ from BAOs and $f_g(z)$ from redshift distortions will provide a direct test of whether cosmic acceleration is due to a modification of Einstein's theory of gravitation or to new physics beyond the standard model.

1.4 Cosmology with high-redshift galaxy clusters

Since clusters arise from rare high peaks of primordial density perturbations, their number densities and mass distribution, i.e. their mass function $n(M,z)$, is highly sensitive to the matter density parameter Ω_M , and dark energy parameters (Ω_Λ, w) which control the rate at which structure grows, as well as to the normalization of the matter power spectrum, σ_8 .

SPACE will provide **spectroscopic confirmation of all clusters detected in the next generation near-IR, Sunyaiev-Zeldovich (SZ) and X-ray large area surveys**. *SPACE* will identify bona-fide virialized structures, those to be compared with the theoretical cluster mass function, and it will resolve the cases of contamination from point-like radio sources and AGN that are expected to plague future SZ and X-ray searches for distant clusters. Thus, *SPACE* will unleash the full potential of the next generation cluster surveys by allowing the best possible knowledge of systematic errors, with small statistical uncertainties limited only by the volume of the observable Universe. In addition, *SPACE* itself will locate for the first time several tens of thousands of clusters directly in three dimensions out to $z\sim 2.5$ and over a large mass range. By comparing these galaxy concentrations with SZ and X-ray maps we will be able to monitor the relative baryonic content in the hot and cold phase out to $z\sim 2$, an epoch when the gas is thought to first thermalize in the potential well of massive clusters.

The *SPACE* cluster survey is a natural by-product of the *SPACE* All-sky spectroscopic survey and has a size that makes it **competitive with any dedicated cluster survey**. At the same time, it will provide a complementary measurement of the cosmic history of structure

growth adding an invaluable cross-check of the results obtained also with *SPACE* on galaxies.

1.5 Galaxy Evolution as a Function of Environment

By observing galaxies down to faint magnitudes, *SPACE* will measure the characteristics of **more than half a billion galaxies as a function of their environment at sensitivities impossible to obtain from ground-based telescopes.**

The strong optical-ultraviolet spectral features of galaxies well below L^* that are primary redshifts and diagnostic tracers fall, in the redshift range $z \sim 0.5-3$, in the near-IR. Their list includes: Balmer and D4000 continuum breaks, strong H Balmer lines, CaII H&K lines, as well as the well-studied diagnostic emission lines such as [O II] λ 3727, Balmer lines, [OIII] λ 4959,5007, and several high ionization lines useful for identifying the presence of an active galactic nucleus. At higher redshifts, *SPACE* will obtain redshifts and diagnostics of the young stellar populations and the interstellar medium using rest-frame ultraviolet lines.

Examples of investigations enabled by the main *SPACE* survey include:

- To provide a complete **census of galaxies** independent of their type and measure the evolution of the distribution functions (e.g. luminosity, stellar mass) significantly below the characteristic mass, M^* . *SPACE* observes passive galaxies from $z=1.5$ to their formation epoch.
- To investigate how the properties of galaxies depend on the density of their surroundings. From the relative velocities of many galaxies, one can define mass concentrations dynamically and probe environmental densities and evolution with epoch.
- To determine the **merger rate** as a function of redshift.. These data also provide a check on the use of galaxy-galaxy lensing statistics to estimate total halo masses and profiles.
- To determine **black hole masses** and compare them to the stellar content, mass, and age of the host galaxy, probing feedback processes in the largest high- z sample of AGN ever.
- Determine the causes of “**downsizing**”, whereby star-formation histories correlate with stellar mass, and active sites move to increasingly higher mass galaxies with redshift.
- Ideally complement **LSST**, in particular for weak lensing science, and in general enable new facilities such as **LOFAR, eROSITA, WISE, SKA** to reach their full capability by removing the “bottle neck” in obtaining redshifts for large survey samples.

1.6 Type Ia supernovae with SPACE

As we mentioned in the Executive Summary, *SPACE* has an enormous potential if used as an observatory. In particular, a relatively modest investment of time in a Deep Survey could allow *SPACE* obtaining the same number of SNe Ia out to $z=2$ as SNAP in 1/5 of the time (4.8 months for *SPACE* versus 2 years for SNAP). This gain results from the enormous advantage that wide-field multi-slit spectroscopy gives *SPACE* over other missions for obtaining time-consuming spectra of distant SNe. The spectrum of a $z=1.7$ SN Ia requires about 8 hours of exposure on a 2m class space telescope (Aldering et al. 2004). *SPACE* can observe many SNe Ia simultaneously by targeting a deep (e.g. $H < 26$) field of 4 square degrees every 10 days. Obtaining the spectra of all SNe Ia in its 0.4° field of view, *SPACE* will be almost an order of magnitude more efficient than SNAP, for example, in SN spectroscopy. We expect about 2300 SNe to $z \approx 2$ assuming a conservative SN Ia rate (with a delay time between formation of the progenitor and explosion of 3.5 Gyr). If this program is executed, *SPACE* will obtain multiple spectra of the same SNe Ia, which will allow detailed study of systematic effects, and the co-adding of spectra adjacent in time to increase signal-to-noise ratio for the highest redshift SNe Ia. Indeed, *SPACE* will observe more $z > 1$ SNe than SNAP.

II. Technical Overview of *SPACE*

SPACE, originally conceived as a joint ESA-NASA project, was proposed to ESA in 2007 in response to the call for proposals for the first Cosmic Vision 2015-2025 planning cycle. Having received the highest ranking, it was down-selected and merged with DUNE (a dark energy mission based on Weak Lensing) into the *EUCLID* mission concept. As the merging comes at the cost of a loss of performance, we will focus our discussion on the original *SPACE* concept, with improvements in what concerns the optical design.

SPACE is designed to reach the DETF Stage IV FoM using only the conservative “wiggles only” measurement of BAO, robust against systematic uncertainties, and pessimistic assumptions about SN Ia systematic errors. This drives the observational and instrument requirements.

II.1 Infrared Spectroscopy with *SPACE*

The optimization of *SPACE* parameters has been made through extensive simulations of different instrument configurations, varying the criteria for optimal slit positioning and using both real and artificial (from the Millennium Simulations) galaxy catalogs with magnitudes matched to the sensitivity limits of the survey. The best results have been obtained in the near-IR with $4k \times 4k$ HI-1RG detector, pixel scale $0.375''$, $15 \text{ \AA}/\text{pix}$ dispersion, 2 pixels per slit along dispersion, spectrum length of 670 pixel, spectral resolution of 400. This combination allows a sampling of 1 of every three galaxies to $H=23^m(\text{AB})$, a 31% efficiency for a single pass of 15min exposure time on a typical field (Figure 5).

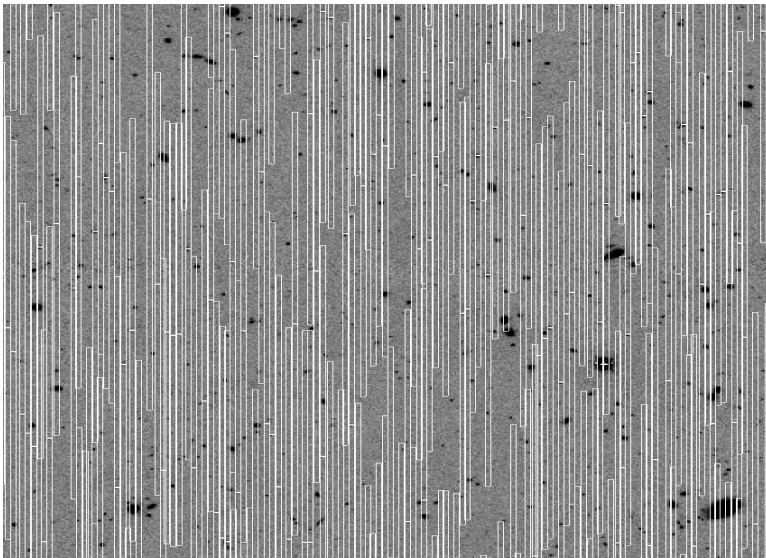


Figure 5: a simulated $5' \times 7'$ field showing the location of the spectra of the selected targets.

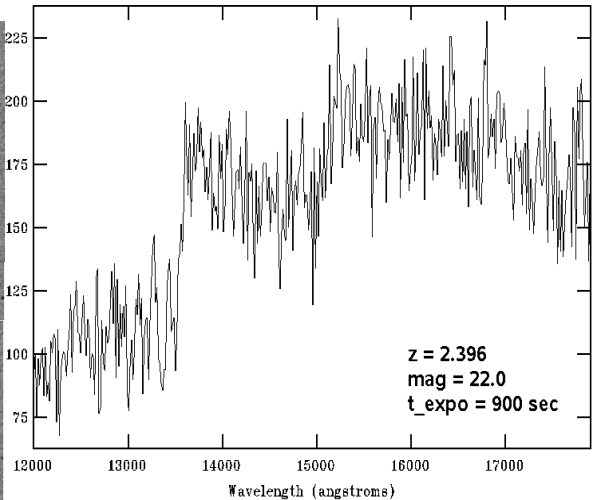


Figure 6. Simulated spectrum of an early-type passive galaxy at $z > 2$. The D4000 break and the main absorption lines (Ca II H & K) are clearly detected. It is impossible to obtain such a spectrum with ground-based near-IR spectroscopy due to the sky background and OH line contamination.

Assuming these optimal parameters, template spectra were used for all galaxies types, accounting for the proper function of magnitude and redshift. The results show that the dispersion and the resolution of *SPACE* are adequate to reliably identify the main emission

and absorption features of all galaxy types (Figure 6). The low background, wide wavelength coverage, and moderate spectral resolution produce a success rate of spectroscopic redshift measurements between 80% – 99% for integration times of 900 sec regardless on galaxy types and redshifts. Typical accuracy on redshifts is $\sigma_z \leq 0.001$.

II.2 *SPACE* Science program

SPACE can execute a **Core Program (~4 years)** and **allow for Guest Observer Programs**.

Assuming the baseline configuration, the Core Program can be envisioned as follows:

The *SPACE all-sky survey* covers the full sky at galactic latitudes $> \pm 18^\circ$ (~70% of the total). This corresponds approximately to 28,500 square degrees, i.e. 71,000 fields (0.4 deg²/field) or 100,000 fields assuming 30% overlap between tiles. With 20 minutes per pointing, with an observing efficiency of 75% (15min on source), 100,000 fields requires 3.8 years. At $H=23^m(\text{AB})$ there are approximately 50,000 galaxies per square degree. The expected number of galaxy spectra with a 1/3 target random sampling is therefore of the order of $(50,000/3) \times 71,000 \times 0.4 \approx 0.5 \times 10^9$ (1/3 larger if the overlapping areas are used to observe different galaxies).

The selection of the spectroscopic targets can be done by taking a broad-band (J+H) acquisition image at $\text{AB} \sim 24$ immediately before the spectroscopic observation. Targets are selected using onboard software similar to the one currently adopted in ground-based spectroscopic surveys (e.g. VVDS, zCOSMOS). As a byproduct, the acquisition images produce the deepest all-sky imaging survey ever at $|b| > \pm 18^\circ$. Alternatively, or as a complement, one can upload target list catalogs (e.g. from LSST).

GO programs could include a SPACE Deep Survey. A deep survey could target a 10 deg² field (25 *SPACE* pointings) down to $H(\text{AB})=25$, with a target sampling rate of 90%, and without any color pre-selection. About 200,000 objects (stars+galaxies) are expected in 1 deg² at $H < 25$. With a multiplex of ≈ 6000 objects and an integration time of about 7 hours per observation to reach a sufficient S/N, one needs $\approx [(200,000 \times 0.4 \times 0.90)/6000] \times 25 \text{ pointings} \times 7\text{h} \approx 5$ months. Galaxy candidates at $z > 7$ can be pre-selected using the *SPACE* imaging in z,J,H bands and will be “compulsory” targets repeated in each of the 12 spectroscopic observations done for each of the 25 pointings so that they will accumulate a total integration time of $(7\text{h} \times 12) = 84$ hours (per pointing) needed to reach a sufficient S/N for J, H = 26. The time needed for the broad z, J, and H bands and narrow-band imaging will be negligible with respect to the time dedicated to spectroscopy. With an appropriate strategy of repeated visits, the Deep Survey could be used also for detecting high-z SNe.

Allocating a fraction of the time to **Guest Observer Programs** adds value to the mission. The Core Science program could be split in four phases lasting approximately 9 months each, allowing the GO observing time to be ramped up over time in a manner similar to the phasing in past missions such as ISO and Spitzer. In this way the core science program can be completed in a timely manner while providing the community with early instrument performance information to use in the planning of observations for other studies.

II.3 System design

SPACE performs multi-object spectroscopy in the near-IR. To achieve its sensitivity requirements, *SPACE* operates in slit mode, fully exploiting the celestial background from space ~ 500 times lower than from the ground. The telescope diameter is set a 1.5m, and the field of view is of 0.4 square degrees. Other key parameters are listed in Tables 1 and 2.

**Table 1: *SPACE*
MISSION PARAMETERS**

Telescope diameter	<i>1.5m</i>
Optical configuration	<i>Ritchey-Chrétien</i>
Wavelength range	<i>0.6-1.8 μm</i>
Optical quality	<i>Diffraction limited $\lambda > 0.65\mu\text{m}$</i>
Pointing stability	<i>0.1" rms/ 30min</i>
Overall mass	<i>1486 kg</i>
Data rate	<i>1.5Mbit/s</i>
Orbit/Launcher	<i>L2/Soyuz</i>
Launch date	<i>Mid 2017</i>
Mission Duration	<i>5 years</i>
Partners	<i>ESA-NASA-European Agencies</i>

**Table 2: *SPACE*
INSTRUMENT PERFORMANCE**

Total field of view	<i>51' x 27' (0.4 sq. degree)</i>
Nr. and type of DMDs	<i>4 CINEMA chip (2048x1050)</i>
Total nr. of mirrors	<i>8.8 million</i>
Mirror field of view	<i>0.75" x 0.75"</i>
Number of spectra	<i>~6,000 simultaneous</i>
Detector Pixel size	<i>0.375" x 0.375"</i>
Dispersing element	<i>Prism R~400; 0.8-1.8μm</i>
Imaging filters	<i>z, J, H, narrow band</i>
Detector	<i>HgCdTe 0.4-1.8μm, 2k x 2k</i>
Nr. of detectors	<i>16 (4 mosaics of 2x2 chips)</i>
Detector Temperature	<i>~145K</i>
QE	<i>>75% average</i>
Readout noise	<i>5e/multiple read</i>
Observing modes	<i>Wide field imaging, slit, slitless and integral field spectroscopy (Hadamard)</i>

To efficiently perform multi-object spectroscopy, *SPACE* uses Micro-Electro-Mechanical-Systems (MEMS) technology. Instead of the Micro-Shutter-Arrays (MSA) used on JWST/NIRSPEC, *SPACE* uses Digita-Micromirror-Devices (DMDs). DMDs provide exceptional reliability (more than 18 million parts have been build by Texas Instrument) and come in format up to 2048 x 1080 randomly selectable micromirrors, more than 35 times the number of slits in a MSA. DMDs are not new to astronomy: a DMD based IR spectrograph, IRMOS, is in operation at the 4m telescope at KPNO.

DMD based spectrographs are extremely versatile, as they allows for different observing modes depending on the DMD configuration and on the presence or not of a dispersing element in the pupil filter wheel (the only moving part of the spectrograph). A DMD-based spectrograph can perform imaging (all mirrors ON+filter), slitless spectroscopy (all mirrors ON+prism), slit spectroscopy (slit of mirrors ON+prism), multi-object spectroscopy (random constellation of mirrors ON+prism), and even wide-field integral-field spectroscopy using Hadamard transforms (multiple combinations of slits ON+prism). More informations on DMDs are provided in Section 3.

To achieve a large field of view, multiple spectrographs are needed. Originally *SPACE* envisioned four identical spectrographs, each one taking a fraction of the telescope focal plane delivered by a pyramid folding mirror. The optical design of the spectrographs originally proposed for *SPACE*, based on all-reflective optical system, achieves excellent performance at the price of relatively large sizes. Recently, progresses have been made toward the design of much more compact systems. In Figure 7 we show the layout of a DMD spectrograph based

on refractive elements. A key component is the Total Internal Reflection prism placed immediately before the DMD, which folds the reflected beam nearly 90 degrees from the incoming beam. This is the solution commonly implemented in DLP projectors, which are in general extremely compact (the most recent models fit into cellular phones!). Several spectrographs like the one shown in Figure 7 can be accommodated around the focal plane of the telescope. The field of view covered by a single spectrograph depends on the $f/\#$ of the incoming beam. TIR prisms normally work at $f/2.4$. For a 1.5m telescope, a 0.4 square degree field requires 4 spectrographs at $f/2.5$. There is a trade-off between the cost/performance of a spectrograph working with fast $f/\#$ number and the number of spectrographs: it may be more convenient to have e.g. 6 spectrographs at $f/3$ than 4 at $f/2.5$. Having more spectrographs also allows observing a higher fraction of sources per exposure. The assessment of these trade-offs is still ongoing.

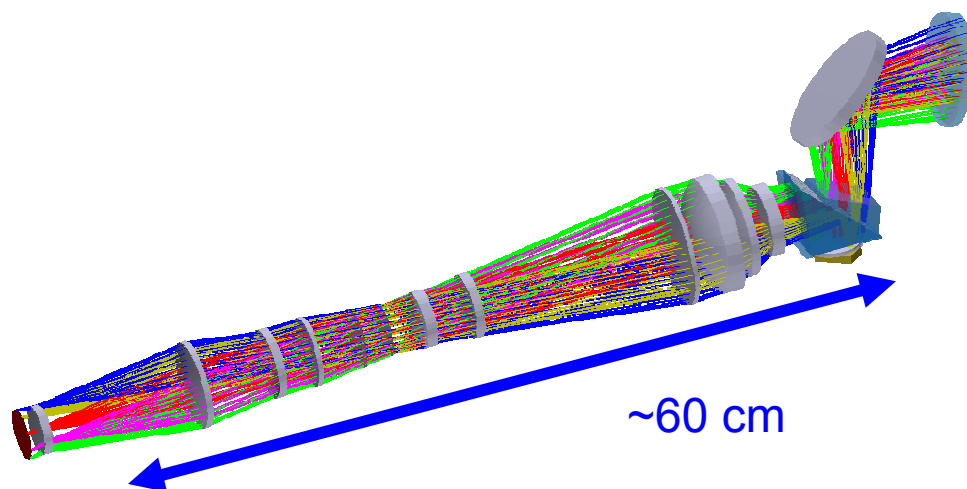


Figure 7. Optical layout of a DMD-based spectrograph based on refractive elements. Note the Total Internal Reflection prism placed immediately before the DMD, which folds the reflected beam nearly 90 degrees from the incoming beam.

Regarding the detectors, *SPACE* has been baselined with the standard HgCdTe HI-2RG 18micron size devices. For optimal sampling, a 4kx4k Focal Plane Array is ideal, but a 2Kx4K mosaic is acceptable. Teledyne has already developed monolithic 4kx4k devices with 10micron pixel size. Concerning the cutoff wavelengths, one can exploit passive cooling at L2 to achieve temperatures compatible with 2.5micron parts, avoiding the risks and costs of the more challenging 1.7 micron devices developed for WFC3.

The other parts of *SPACE* are conventional, with the exception of the onboard computing capabilities which are superior to e.g. JWST. *SPACE* must be able to perform a number of SW operations, in particular a) pre-processing of astronomical images, including identification and removal of cosmic rays, ramp fitting and flat fielding for target acquisition; b) target selection, possibly including cross-checking with uploaded catalogs. Having computing capabilities onboard allows for ultimate data quality, high signal-to-noise ratio and minimizes the volume of raw data to be downloaded to ground, freeing precious and expensive DSN resources.

II.4 Observing with *SPACE*

A typical *SPACE* observations is sketched in Figure 8. After locking the guider, a ~30s broad-band image is taken and corrected for bad pixels, cosmic rays and flat fielded using calibration frames stored on-board. The software then selects the targets and generates the optimal DMD configuration. In the mean time, a prism is inserted at the place of the broad-band filter. We allocate 5 minutes for these operations.

The versatility of DMDs and modern IR detectors allow for further refinements. For example, one can split the integration to optimize the extraction of the bright sources, possibly using the subarray modes of the detector.

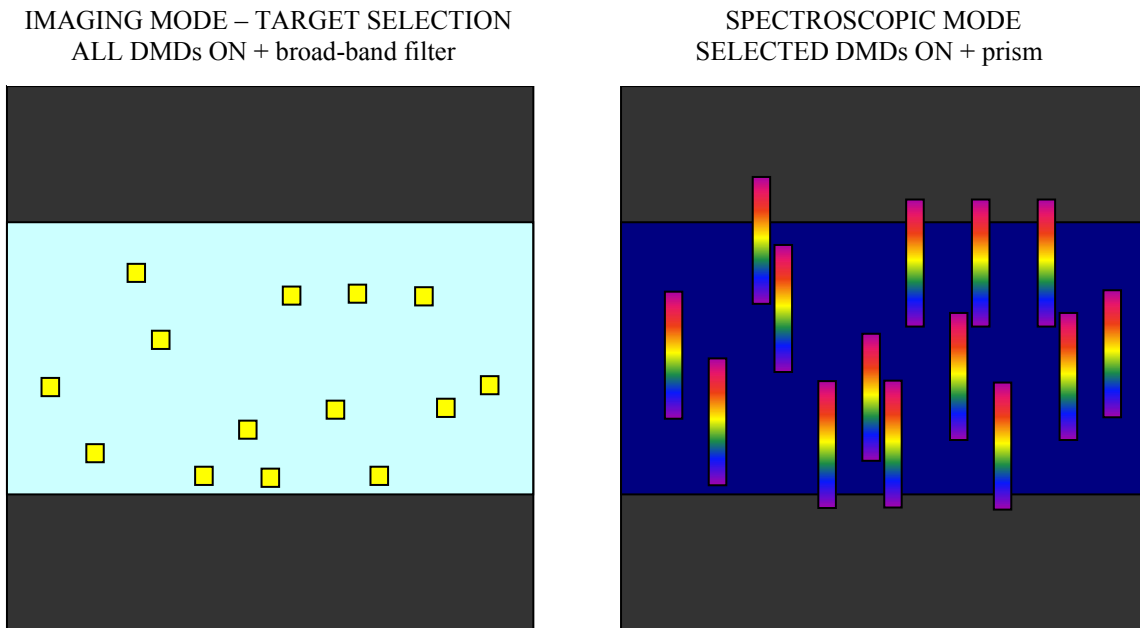


Figure 8: sketch of the data acquisition and observing procedure. Left: the DMD field is projected onto the detector (dark background) in broad band imaging mode. The light blue color indicates the high background, targets are represented by yellow squares. Right: all DMDs are turned off except those of the targets, the prism is inserted. The background is low (dark blue) and spectra are produced.

Extensive experience with IRMOS at KPNO provides clear guidelines on the calibration strategy with *SPACE*. Raw data (both spectroscopy and imaging) require standard calibration files: bad pixel masks, dark, flat-field and wavelength calibration. Of these, flat-fields are the most critical. In spectroscopic mode flat fields can be obtained by flashing at the end of each exposure the same DMD configuration used for taking science data. This short flat exposure with the DMD still “on source” provides an excellent flat field for each target, close in time to the science data. Exposure after exposure, the collection of flat fields grows to the point that a template solution can be built. This may be applied later in the mission without the need of new exposures. Spectral (wavelength) calibration will require only sporadic checks. Concerning astrometry, one calibrates the field distortion at the focal plane using standard astrometric fields (e.g. globular clusters, or the LMC). The map between the DMD mirrors and the detector pixels must be stable and accurate, as it is critical to select the targets. It can be easily obtained by illuminating a DMD set with a rectangular grid pattern. Spectrophotometric standard stars are used to calibrate spectra in absolute flux units.

III. Technology Drivers: DMD

III.1 Current status

The innovative aspect of the *SPACE* mission is the use of DMDs. Since their invention at Texas Instruments (TI) in 1988, DMD have been serially produced with volumes exceeding 18 million units shipped by 2007. Today DMDs represent the leading technology in digital imaging (DLP projectors). For this multi-billion dollar market TI has made huge investments, reaching unique levels of quality and reliability.

TI produces several types of DMDs, sealed in hermetic packages. The *SPACE* baseline assumes the 2048×1080 pixels “CINEMA” device with 13.68 μm pixel pitch, 0.68 μm gap width. Each micromirror, independently controlled, can switch along its diagonal by $+12^\circ/-12^\circ$ as a result of electrostatic attraction between the mirror structure and the underlying circuitry. The mirrors can flip at several kilohertz for trillions of cycles. **In many respects, DMDs are the most reliable machines ever made.**

A full account of the current status of DMD applications for Astronomy has recently be given (Robberto et al. 2009). From the point of view of optical performance (diffraction losses, emissivity, contrast, image quality, coating) commercial DMDs match all requirements of a mission like *SPACE*. ESA is currently carrying-out the space qualification in collaboration with research institutes in Europe (LAM-Marseille, INAF Bologna) and results are expected later this year. The maturity of this technology, together with the proper characteristics of nano-technology (nanoscale fatigue and fracture of the mechanisms is virtually absent, extremely high resonant modes are decoupled from the frequencies encountered during launch, etc) give us confidence that no showstopper will be found.

Possibly the most sensitive area are not the DMDs themselves but their control software and electronics, which are based on TI proprietary technology. ESA, working in close collaboration with Visitech, a Norwegian company world leader in the development of DMD-based systems, has successfully circumvented this issue with a number of workarounds and modifications to the custom part of the driving software. However, NASA could be in a better position to directly negotiate with a US company like TI a more direct solution.

III.2 New developments

NASA/Goddard and DoE/Sandia National Laboratories started years ago the development of DMDs for JWST. When the Micro-Shutter-Array were selected for NIRSPEC, this effort was halted (at least in the US, as it is progressing in France, see Waldis et al. 2009).

Like Infrared Detectors, **DMDs represent a crown jewel of USA technology.** Considering their maturity, we believe that NASA should seriously consider the possibility of resuming the development of DMDs directly designed for astronomical applications. Commercial DMDs like those we plan to use in *SPACE* have small pixel size which makes them less than ideal for very large telescopes. Ideally, micromirror sizes larger than 13 micron, DMD formats larger than 2kx1k and the possibility to operate at $T < 50\text{K}$ for mid-IR astronomy would enable a new generation of astronomical instruments with unprecedented capabilities. As these parameters have little commercial interest, an independent development is required.

IV. Activity Organization, Partnerships, and Current Status

Originally conceived in the US, *SPACE* has been proposed by a joint European-US team in response to the Call for Missions for the first ESA Cosmic Vision 2015-2025 planning cycle (PIs A.Cimatti, University of Bologna and M. Robberto, STScI)

The ESA Advisory Structure has recognized Dark Energy as the most timely and important science topic among the medium class (“Class M”) mission proposal and recommended it as the top priority. In particular, the ESA Astronomy Working Group expressed “a slight preference for *SPACE* over the imaging *DUNE* mission, but it felt that a better informed decision on the best approach for an European Dark Energy mission should be taken”. In October 2007 ESA selected both mission for further assessment and almost immediately merged them into the *EUCLID* mission, with goals and boundaries set by an ad-hoc team, the Concept Advisory Team headed by Prof. M. Longair.

In parallel, a basic feasibility “phase 0” study was carried-out by ESA leading to a very preliminary design for the *EUCLID* mission and its payload. What was *SPACE* is now the ***EUCLID-Near Infrared Spectrograph (ENIS)***. To keep the *EUCLID* concept within the envelope of a (expanded) Class M framework, ESA limited the number of NIR detectors to ~16 (to be shared between a wide-field imaging channel and the *ENIS* spectrographs) and set the maximum size of the primary mirror to 1.2m. This downsizing has a major impact on the *ENIS* performance, first because the total number of available IR detectors constrains the number of spectrographs to 2 or 3, pushing the optical design to recover field of view, and second because the smaller primary limits the sensitivity of the survey. In May 2008 an Invitation to Tender was issued to the Industry. The report of this assessment study will be presented to the scientific community in late 2009. A parallel competitive contract was awarded to EADS Astrium (Germany) and Thales Alenia Space (Italy).

Recently, the possibility of a further merging of *EUCLID* into *JDEM* has emerged (*IDECS*), *JDEM* being envisioned as the merging of older mission concepts. We believe that this provides an excellent opportunity for a fresh look into the scientific potential and technical feasibility of **a mission like the original *SPACE*, either in a “merged” form or as a stand-alone platform**, with the obvious cost savings that this second choice would imply. In the original *SPACE* proposal, NASA was going to contribute the key technology, DMDs and Infrared Detectors (both made in the USA), setting in exchange a US science center and archive that we envisioned hosted by STScI. NASA has now the possibility of playing **the leading role** in this wonderful mission, knowing that it has **already passed the approval of ESA’s advisory structure and a number of Space Agencies of the European Member States are definitely willing to support it.**

V. Activity Schedule

a) US leadership in the field of DMD-based astronomical instrumentation

We recommend that NASA regains the leadership in the field of astronomical instrumentation based on DMD devices, starting immediately a vigorous and effective program aimed at:

- 1) The space qualification and performance assessment of commercial DMD devices and their driving electronics
- 2) The development of the next generation of low-temperature/wide-format DMDs specifically designed for astronomical instrumentation

b) *SPACE* and *JDEM*

We recommend that NASA evaluates the enormous benefits that DMD technology brings to the scientific case for the *JDEM/IDECS* mission. The preliminary design study currently in progress should consider the possibility of having a DMD-based spectrograph(s) as the *baseline* for *JDEM/IDECS*, looking behind the simple merging of pre-existing concepts. Alternatively, a mission like *SPACE*, capable of attacking the dark-energy problem using at the same time BAO, growth factor, cluster counts and even SNe techniques, together with providing an enormous return for general science, could be evaluated as a stand-alone, US-lead project. Such a mission could actually provide the best return in terms of “science-per-dollar”.

DMDs may definitely provide also the baseline for future, larger space missions, like the Galaxy Survey Space Telescope (GSST) proposed in another RFI (*Large-Scale, Spectroscopic Galaxy Surveys With a 4-m Space Telescope*, by S. Heap & M. Robberto). We point to the RFI for GSST for a list of suggestions regarding the activities that NASA should carry out for Space Qualification, Performance Testing and Ground Based development of DMDs and their related instrumentation.

Concerning the evaluation of a *SPACE*-like mission, our team has been deeply involved in the definition of the original *SPACE* proposal and still closely collaborates with the European team in the phase-0 study of *ENIS*. Having gained unique expertise, we are willing to support all initiatives that NASA may undertake to independently assess the feasibility and scientific potential of our proposed mission.

VI. Cost Estimates

SPACE was originally designed within a total cost cap for ESA of 300MEuro (2007). In our initial proposal, the total ESA costs, including spacecraft (a relatively cheap Soyuz launcher) and payload were estimated to be \$264M€. To this amount, one should add the costs to NASA (42M\$) and the costs to the European Space Agencies, estimated at \$33M€. This last amount does not include substantial manpower contribution from the science staff of European research institutes.

Hereafter we present the **breakdown of the original ESA proposal**, converted to US dollars. The use of a US launcher and full cost accounting may increase this estimate by ~30-50%.

Payload/Instrument costs (2007)

<i>Item</i>	Cost (M\$ 2007)
1. Pre-implementation phase (30 FTE, based on ESA estimates):	9
2. Bus/telescope	
2.1. Telescope assembly (mirrors & structure)	20
2.2. <i>SPACE</i> SVM (Service Module – bus)	84
2.3. Instrument Electronics:	42
2.4. Instrument System & AIV activities:	13
3. Payload	
3.1. Optical elements	7
3.2. Mechanical support for optical elements, optical bench:	4
3.3. Filter wheel mechanism	2
3.4. Calibration system	3
3.5. DMD and relative control	4
3.6. Thermal control, harness	2
3.7. Test and alignment facility	5
4. Detectors	
4.1. Detector procurement: 500K\$/device × 32 devices	16
4.2. Sidecar ASICS and control electronics:	5
4.3. Software development	4
4.4. Flight packaging	10
5. Launch services: Soyuz-Fregat	60
6. Ground Segment (Mission/Science Operation Centers)	60
7. Program Management	15
8. Outreach	7

10.4 Overall Mission costs

Estimated cost	372
30% contingency	112
Total cost including 30% contingency	484

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