DWARFS - Diverse Worlds ARound Faint Stars

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1 Abstract

The Space mission DWARFS is designed to determine atmospheric composition and physical properties of rocky extrasolar planets in the habitable zone around M-Type stars. Most importantly, we want to research the atmospheric composition with a special emphasize on O_3, H_2O, CH, CH_4, CO_2, CH_3Cl lines, as well as the evolution of the planetary systems. For some of the stars DWARFS will be able to detect in addition surface features, moons or further planets in the system. All this will be done with two spectrographs in the NIR/MIR and a photometer (r, i SDSS) in a 4m space telescope.

2 Introduction

The field of extra solar planet research evolves with an amazing pace – since the first detection in 1995, by now more than 350 exoplanets were detected using various techniques. As ongoing and future surveys are expanding their limits further towards low mass planets, a large number of rocky planets similar to our Earth are foreseen to be detected in the near future.

Though detection techniques usually provide only basic planetary parameters (e.g. orbital elements, mass, radius and density), space missions such as the Hubble Space Telescope (Charbonneau et al. 2001, Brown et al. 2001) and Spitzer (Harrington et al. 2006) have most recently been able to probe the atmospheres of transiting planets. This can either be done by investigating the partial absorption of starlight when the planet passes in front of the star (primary transit) or by comparing the combined spectrum of planet and star with that of the star alone once the planet hides behind it (secondary eclipse). However, current missions are only capable of resolving spectra of "Hot Jupiters", or "Hot Neptunes" at most (Tinetti 2008). Characterizing small, rocky Earth-like planets will be a challenging task for future missions.

Big next-generation telescopes such as the E-ELT will provide valuable spectral information of extra-solar planets in the visible and near-IR from ground (Kaltenegger & Selsis 2009). However, many important spectral features and so-called "biomarkers" are found in the mid and far IR range, which is basically inaccessible from ground and will therefore need to be investigated by future space missions with high-resolution spectroscopy. In particular, the James Webb Space Telescope (JWST) will be able to characterize transiting Earth-like planets in the spectral range from 0.6 to 27μm (Kaltenegger & Traub 2009).

3 Scientific Motivation

The DWARFS space mission is designed to characterize rocky planets orbiting M-type stars within the iceline and habitable zone, and to understand the atmospheric evolution of these class of planets. The primary scientific objectives can be summarized as follows:

- Investigate if Earth-like atmospheres can evolve in rocky planets in the habitable zone around M-type stars.
- Detect spectral biomarkers.
- Study planetary evolution in an M-type star sample.
- Use this evolution to characterize M star planet

atmospheres as a proxy for active G-type star systems.

In the solar neighborhood, 75% of all stars are expected to be M dwarfs (Guinan & Ingle 2009). Being fainter, the range of planetary orbits where liquid water might exist (the so-called ”habitable zone”) is located much closer to M-type stars compared to larger stars like our Sun. However, due to the active nature of M-type stars, most of the planets within the habitable zone are highly irradiated by strong ultraviolet (EUV) and soft X-ray (SXR) radiation. Despite the large number of M dwarfs, it is still completely unknown if and how atmospheres can form and survive in these extreme environments. Our mission will thus form a first milestone towards a better understanding of exoplanets the most abundant stellar species in our galaxy.

It is important to monitor possible periodical changes in the time of the transit because short-term variation (1-100s) in the mid-time of the transit can be caused by the presence of other exo-planets or moons in the system (Holman & Murray 2005, Agol et al. 2005). On the other hand, potential long-term changes in the duration of the transit may be the consequence of orbital precession of exo-planets. These effects might have important impacts on the habitability of Earth-like planets.

By investigating the infrared spectrum from 2 to 20 μm, the existence of many important biomarkers (O_3, H_2O, CH, CH_4, CO_2,CH_3Cl) (Kaltenegger & Traub 2009) can be constrained. Some of the planets may show spectral features similar to those observed in the transmission and emission spectra of the Earth. Should these similarities be discovered, they could prove to be one of the first coherent confirmations of an ”Earth-Twin” planet. Characterizing this class of planet is our mission’s primary scientific objective, and would prove to be an extraordinary discovery for the astronomical community and ignite broad public interest. Other planets of our own Solar System, such as Venus or Mercury, may also share similar spectral features to these newly discovered planets. But most intruging of all, this mission will enable us to characterize exotic and unknown worlds. Investigating the extreme environment of M-type stars will thus highly increase our knowledge of planetary habitability, and could give us a deeper insight into how this complicated process works.

The study of a large sample of M-type stars will provide us with planets in different stages of their evolution. By analyzing their spectra we will be able to link atmospheric composition to planetary evolution (see 5). Hence, the comparison of observational data with theoretical models will for the first time constrain the most important dynamical processes in atmospheres of rocky exoplanets.

As a young star, our Sun was very active and thus very comparable to M-type stars (see 2). By studying the sample of planets around M stars, we could therefore advance the evolutionary models of planets around G-type stars, like our Sun, at an early stage of its life. This so-called ”proxy” approach could thus give us a valuable insight into the history of our own planet.

4 Methodology

In order to achieve our scientific goals, we plan to take transmission and emission spectra of transiting planets in the infrared from 2 to 20 μm. As the acquisition of such spectra with a sufficient signal-to-noise ratio (SNR) requires very long integration times, even the most advanced future missions such as the JWST will only be able to observe very few targets. However, a dedicated mission like DWARFS can characterize many exo-planets of different kinds and therefore yield a much broader understanding of planetary evolution and diversity.

During the primary transits we plan to obtain spectra by short time exposures that will be added together. In this way, we have an integration time that covers practically all the primary transit. To obtain the transmission spectra of the planet we must substract the spectra of the star alone, and therefore we must have exposures for the secondary eclipse, too. To achieve higher SNR, we plan to combine multiple spectra of multiple transits, the exact number depending on the distance to the star and the spectral type. As an example, for the 3.3 microns H_2O feature we can achieve a SNR of ≈ 7 for an M0 star and ≈ 30 for an M9 placed at 15 pc with and orbiting Earth-radius planet using a co-added observation time of $\approx$200 hours. Our methodology does not need to resolve the system, as we are based on subtracted spectra. By this way, we do not exlude planets orbiting very near to the star, in particular those in the habitable zone.

For some favourable cases (late type, nearby M stars), we plan to obtain emission spectra as well. To do that we have to expose during secondary eclipses as well. As the required integration times are higher to achieve a sufficient SNR, we expect that we can only do this for few targets. However, due the extreme ultraviolet (EUV) and soft X-ray (SXR) radiation might extend the size of the atmosphere (from 1 R_e to 5 R_e), increasing the emitting area and thus yielding a higher expected SNR compared to a typical Earth size planet. We plan to use two spectrometers with resolving powers of $R = 100$ and $R = 600$, respectively. This approach would allow us to better characterize spectral features for bright targets in our stellar sample.
Because M dwarfs are smaller than our sun, planets transiting around them shield a larger fraction of light during transit and are easier to detect. Combined with a high geometric probability $p_g \approx 5\%$ for transits in the habitable zone ($p_g = 0.005\%$ for Sun-Earth, for contrast), by far the most transiting rocky planets with favourable conditions for life are foreseen to be detected around M-type stars. Surveys such as the MEarth project (Irwin et al. 2009) will search for $N_* \approx 3300$ M dwarfs within 30 pc in the Northern Hemisphere. Considering future surveys in Southern Hemisphere, we expect within the next 10-20 years a sample of $N_* \approx 6600$ suitable M-type stars on the whole sky. Assuming that $f_{pl} = 30\%$ of all stars harbour planets (Mayor et al. 2003) and the surveys detect only $f_{det} = 35\%$ of them due to detection and dutycycle limitations, we estimate a total number of $N_t = N_* \cdot f_{pl} \cdot f_g \cdot f_{det} \approx 30$ known rocky transiting planets by the time our mission will be launched.

By obtaining additional milli-magnitude photometry with very short integration times, we will be able to study Transit Timing Variations (TTVs). These may result from the presence of other planets or moons in the planets proximity (Holman & Murray 2005). With a 4m telescope we can obtain high time resolution light curves ($\approx$1s) of exoplanets orbiting M4-M9 stars.
Furthermore, the comparison of amplitude differences in the resulting light curves taken in different passbands, the height of the atmosphere can be calculated. These kind of results can be used to confirm already existing atmospheric theoretical models, where much larger atmospheres than Earth's are predicted (of the order of 1-5 Earth atmospheres) for planets around very active stars.

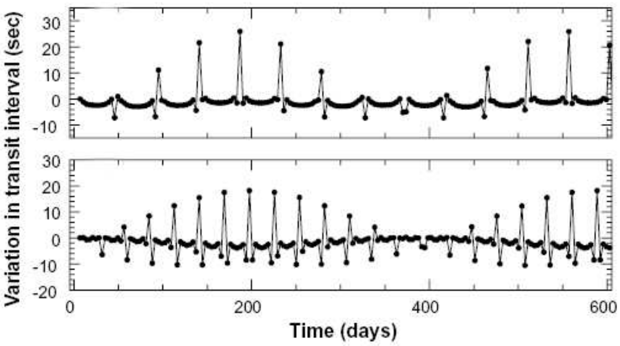


Figure 1: TTV can show us the presence of other bodies in the system (Holman & Murray 2005)

In addition to characterizing planetary atmospheres, we can determine some properties of surface composition by comparing the observed transmission and emission spectra. These could include a solid or liquid surface or presence of amorphous silica ($\approx$10 microns). By means of a precise analysis of the light curves, and due to the quality we expect to have, we also intend to detect differences between the night and day side of the planet, therefore obtaining information about the heat transfer in the atmosphere (Harrington et al. 2006).
We furthermore plan to include higher mass transiting planets (Neptune-like) orbiting around G, K and M stars, as the characterization of a wider mass range can allow deep knowledge of the formation mechanisms of planetary systems, with special attention on multiple planetary systems. We expect that in the next 10 years some planets orbiting L type stars will be discovered. These new exotic systems would be also included in our sample, so we can give some hints on the formation mechanism of these dwarf stars themselves.

5 Payload

5.1 Payload Overview

In order to achieve the scientific goals, *DWARFS* will conduct space-based observation of different orbital phases of transiting extrasolar planets. The major components of the payload are:

- Primary and Secondary Mirror

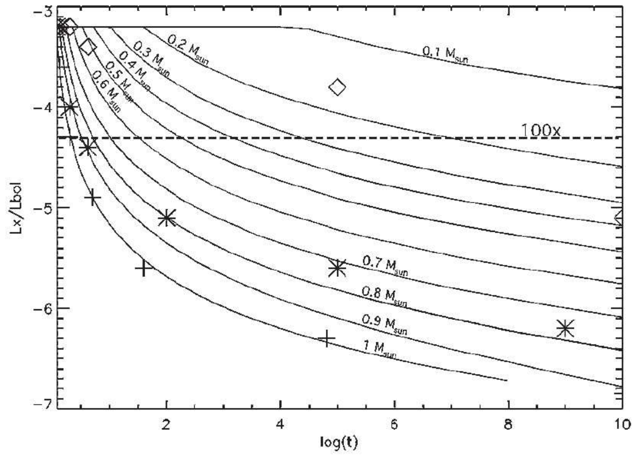


Figure 2: The study of highly irradiated (EUV,SXR) atmospheres of planets around M stars can help us to understand the environment in the young Earth (Scalo et al. 2007)

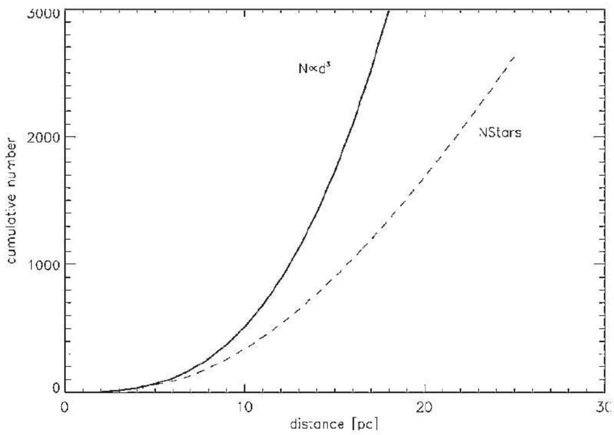


Figure 3: Number of M stars as a function of the distance (Scalo 2007)

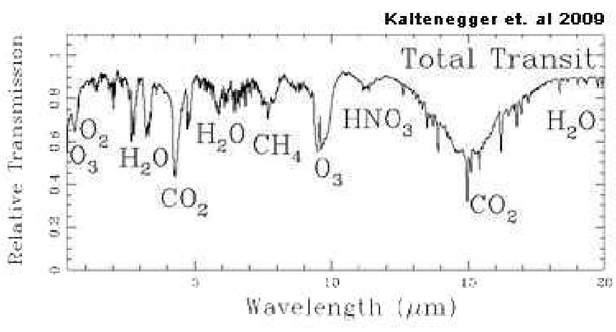


Figure 4: Main features that we can observe in the spectra

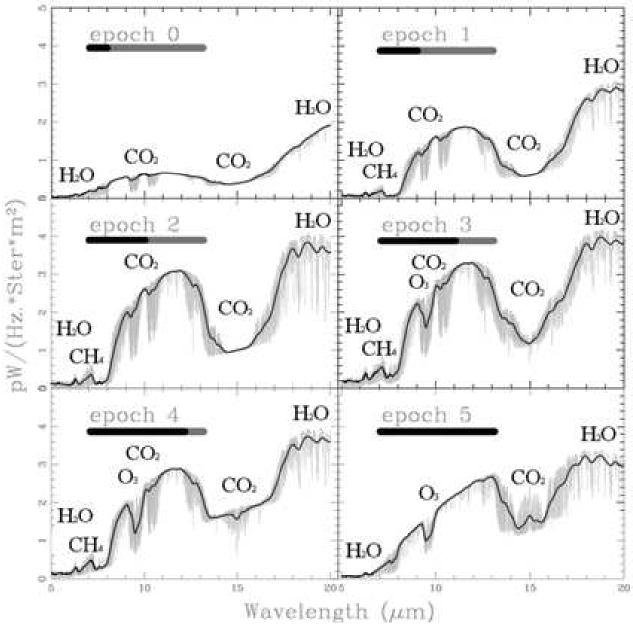


Figure 5: Evolution of the spectrum of the Earth

- Instrument Chamber
- IR Spectrometer
- VIS/NIR Photometer
- Payload Thermal Control

5.2 Primary and Secondary Mirror

The primary mirror used on DWARFS is a lightweight c-SiC silicon carbide construction with an aperture of 4.0m. The secondary mirror is manufactured and processed in the same way. The mirror design resembles the HERSCHEL mirror launched in June 2009 (Sein et al., 2002), but with reduced requirements in terms of figuring errors. To minimize heat exchange between the spacecraft structure, and to provide stiffness and thermal stability, the primary mirror is mounted on six CFRP struts in hexapod configuration.

5.3 Instrument Chamber

The instrument chamber is located around the optical axis underneath the mirror. All detector instruments are accommodated within the instrument chamber. To protect the detectors from damages due to solar and cosmic protons, the wall thickness of the

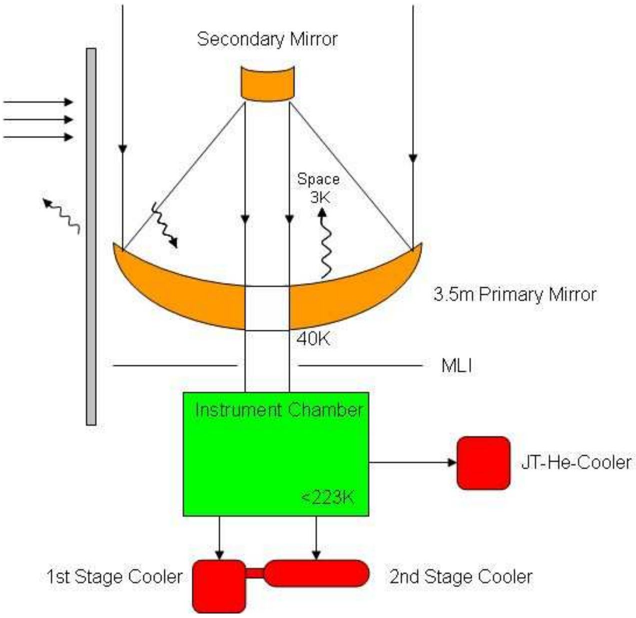


Figure 6: Telescope configuration

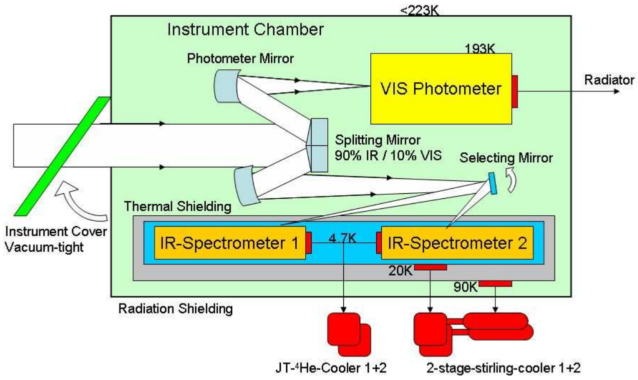


Figure 7: Instrument chamber schematics

IR-Spectrometer 1	
Type	SiAs Detector Array
Bandwidth	$2 - 19.8\mu$m
Resolving power	$100\frac{\lambda}{\Delta\lambda}$
IR-Spectrometer 2	
Type	SiAs Detector Array
Bandwidth	$9.9 - 19.6\mu$m
Resolving power	$600\frac{\lambda}{\Delta\lambda}$

Table 1: IR Spectrometer 1+2 performance

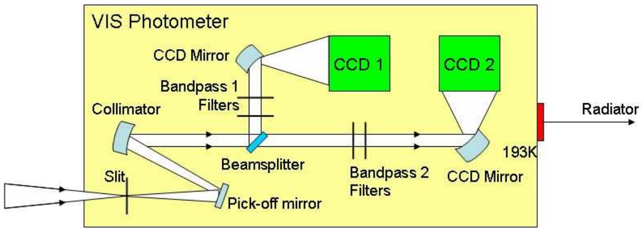


Figure 8: Photometer schematics

chamber needs to be high enough to absorb a sufficient amount energy. To minimize contamination before launch of the instruments, the instrument chamber features a vacuum-tight cover. The chamber also needs to be evacuated and cooled until a few hours before launch.

5.4 IR Spectrometers

DWARFS carries two infrared spectrometers to achieve its scientific goals. Both spectrometers are cross dispersed echelle gratings designed to sample the mid-infrared wavelengths at 2 to 19.8 μm. The detectors are SiAs semiconductors with low dark current and read-out noise.

A redundant selection mirror within the instrumentation chamber diverts the incoming light to one of the two spectrometers. The instruments vary in bandwidth and resolving power.

The basic optical layout, bandwidths and detector materials are similar to the detectors used onboard SPITZER Space Telescope (Houck et. al, 2004).

6 VIS/NIR Photometer

The DWARFS photometer has a two channel camera that provides simultaneous 3’ x 3’ images. Both CCD’s have 265 x 265 pixels where each pixel has a FOV of 0.7” x 0.7”. High speed Commercial-off-the-shelf (COTS) frame-transfer CCD’s with low noise and high dynamic range will be used. CCD1 has a r’-filter (550nm-700nm) and CCD2 has a i’-filter (700nm-900nm). These filters were chosen for differential data evaluation and optimum quantum efficiency.

About 10% of the light coming from the telescope is reflected into the photometer with a geometrical beam splitter and a pick-off mirror. A collimator is used to make the beam parallel. Then, a 50% beam splitter reflects half of the beam onto CCD1 and transmits the

textbfThermal Cooling Power	2×30mW	
Mirror Temperature	40K	
Photometer Temperature	$193\text{K}\pm1\text{K}$	
Spectrometer Temperature	$4.7\ldots5.6\text{K}\pm0$	
Data Rate Photometer	640kbit/Frame	
IR-Spectrometer 1	3.79kbit/Spect	
IR-Spectrometer 2	1.74kbit/Spect	
Mass and Power 2 Sterling coolers	2×15kg	2×90W
2 JT-coolers	2×15kg	2×50W
Instrument Chamber	55kg	
Sun Shield	25kg	
Attitude Control Pointing Accuracy	1arcsec	

Table 2: Payload requirements

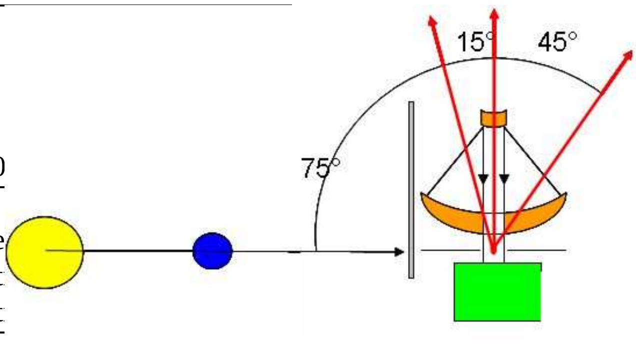


Figure 9: Observation orientation constrains

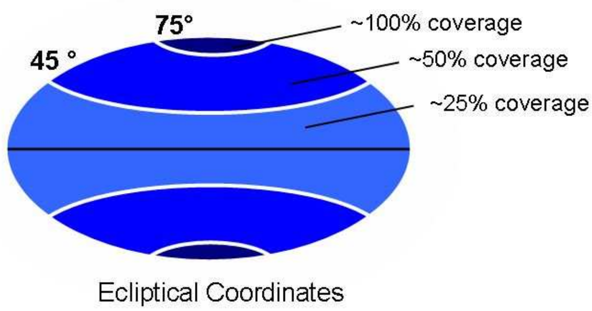


Figure 10: Estimated sky coverage in percentage of mission lifetime

other half onto CCD2. Re-imaging optics (lenses and slits) need to be tailored to limit the FOV and to focus the light onto the detectors. The operation temperature of the photometer is at 193K. This temperature is reached by passive cooling over radiators and heat pipes.

6.1 Payload Thermal Control

Cooling of the instrumentation and the telescope is crucial to the overall payload performance. The telescope mirrors are cooled passively by radiation exchange with deep space to a stable temperature of 40K. The spacecraft therefore needs to support a sunshield that shades the telescope assembly during observation.

To achieve the required temperatures at the detectors, the instrument chamber has different temperature levels. The instrument chamber itself is mounted on thermally insulating struts. A standard heat pipe connected to the spacecraft radiators provides a constant temperature for the Photometer.

The spectrometers require cooling close to absolute zero. A passive cooling system using heat rejection by evaporating liquid He have some major drawbacks in terms of mission lifetime and mass. DWARFS is therefore cooled actively using mechanical coolers. A 2-staged stirling cooler operating at $90K$ and $20K$ is combined with a Joule-Thomson ^{4}He cooler to provide heat rejection of 30mW at 4.7K for the spectrometer sensors. The sensors are passive devices and the heat is dominated by parasitic heat losses. All coolers are fully redundant in order to mitigate single-point failures. A similar, non-redundant cooling system is planned for the upcoming ASTRO-H and SPICA missions (Swinyard and Nakagawa, 2007).

6.2 Observation Constraints

To achieve the required thermal stability, the spacecraft orientation is restricted. The sunshield needs to shade the mirror and therefore needs to face the sun. Observation of targets is only allowed within $-15\,\text{deg}\ldots+45\,\text{deg}$ 9. Considering this constraints, the percentage of sky coverage over the mission lifetime can be estimated as shown in and 10.

7 The DWARFS Spacecraft

7.1 Characteristics

- Mass: 2963 kg at launch (including margin)
- Spacecraft wet mass : 1818 kg (including margin)

- Kick Stage : 1145 kg (including 100 kg kick stage to spacecraft adapter)
- Dimensions : 5.5m high, 4.48 diameter
- Launcher : Ariane 5 ECA or ECB from Guiana Space Center
- Mission Lifetime : 5 years nominal from end of commissioning phase (can be extended)

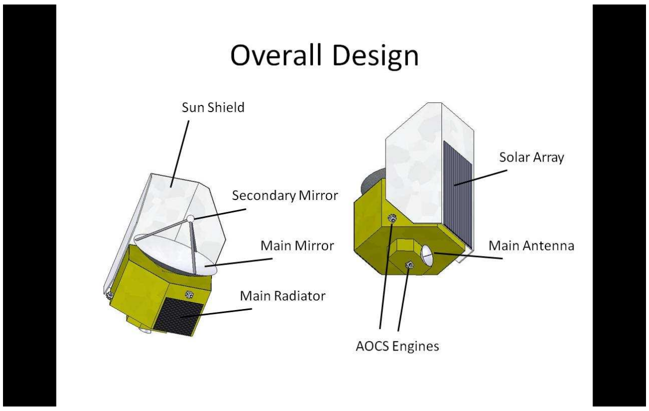
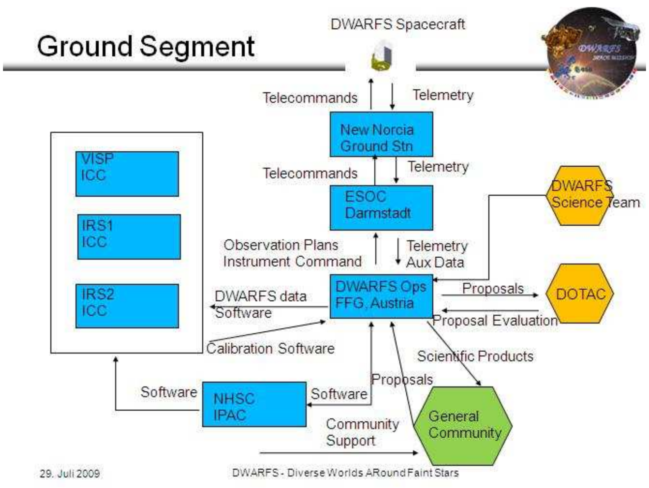


Figure 11: Spacecraft designe

The spacecraft comprises a service module, which houses systems for power conditioning, attitude control, data handling and communications, together with the warm parts of the scientific instruments, and a payload module.
The payload module consists of the telescope, the optical bench, with the parts of the instruments that need to be cooled, i.e. the sensitive detector units and cooling systems. The payload module is fitted with a sunshield, which protects the telescope and cryostat from solar visible and infrared radiation and also prevents Earth straylight from entering the telescope. The sunshield also carries solar cells for the electric power generation.
The service module contains the systems needed to operate the spacecraft:

- Power: The Payload of the spacecraft requires a total power of 345W including 320W for the low Temperature Cooling-system. The Service Module requires up to 149W resulting in an overall Power consumption of 665W including losses and margins. This power is been provided by GaAs solar arrays at the back of the sunshield. Taking into account an efficiency of 19 % and a worst case angle between Solar array and solar radiation of 45° the EOL Power (after 10 yrs) provided by these Solar cells is 145 W/m^2. Therefore 6,5m^2 of solar array is sufficient. Due to the fact that the power consumption of the main components is constant over time, the onboard battery is needed only for safe mode in case of failure and has been dimensioned to store 5kWh resulting in a total mass of 50kg including margins.
- Propulsion: The propulsion system consists of 4 sets of 3 axial monopropellant hydrazine thrusters each providing 30N of thrust with an specific impulse of 220s. These thrusters are mainly used for the station keeping (22.5 m/2 per year), but can also be used for desaturating the reaction wheels. The wet mass of the propulsion system for up to ten years is 200 kg including 10 % margin. These thrusters can also provide enough impulse to make fast maneuvers.
- Attitude and Orbit Control: measurement of the spacecraft's attitude using star trackers, gyroscopes and Sun sensors, and changing the spacecraft's attitude or orbit by means of 3+1-axis reaction wheels and hydrazine thrusters during the 5 year mission, the spacecraft will have to do 200 reorientation with an average of 120° each. Two star trackers (Terma HE-5AS) will be used for the observation phases. These star trackers have the ability to observe faint stars with short integration time. The Therma CryoSat Star Tracker is able to track stars down to Magnitude 6.2 at a slew rate of up to 1° per sec with an accuracy better than 1 arcsecond (pitch/yaw) and 5 arcsecond (roll).
- Control and Data Management: receipt, storage and execution of ground commands, autonomous operation of the spacecraft in the absence of a ground station link, storage and management of observation and housekeeping data
- RF Communications: linking the spacecraft with the ground station to send back data and receive commands. The pointing requirement is of the order of 4° and the data rate is 5 Mbps (frequency 8 GHz, X-band), which enables an SNR of 3.4



- dB. With a contact of 4 hours with the ground station every three days we are able to download up to 8 Tbps of data per year.

- Thermal Systems: The internal heat generation of the system is less than 1kW. Thermal computations showed, that the equilibrium temperature of the spacecraft is 165K considering the effect of the sunshield. therefore an highly radiative area of less than $3\mathrm{m}^2$ is sufficient for thermal management within the spacecraft.

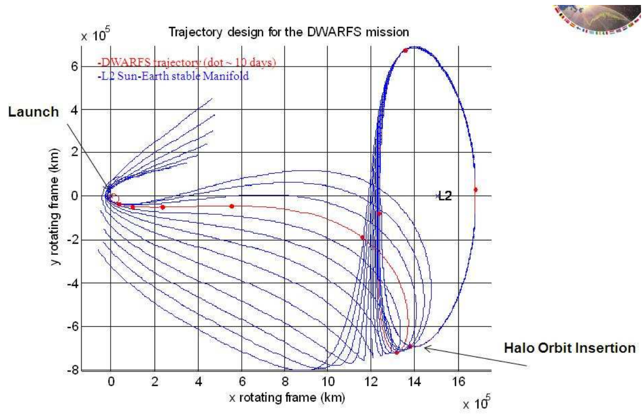
8 Mission Operations

8.1 Launch Information

DWARFS will be carried into space by an Ariane 5 ECA launcher with a shared launch from the Guiana Space Centre, Kourou, French Guiana. It will enter into a GTO parking orbit of 5° inclination. Then, a burn of about 970 m/s (including trajectory correction maneuvers), will put DWARFS into a stable manifold associated with the desired quasi halo orbit. After a journey lasting about ninety days, DWARFS will enter its operational orbit, a large Quasi halo orbit around L2 the second Lagrange point of the Sun-Earth system, 1.5 million km away from the Earth.

8.2 Orbit and navigation

The chosen orbit will take DWARFS about 150 000 km above and below the plane of the ecliptic with a maximum azimuthal excursion of around 700 000 km either side of the Lagrange point. The Earth to spacecraft distance will vary from approximately 1.2 to 1.8 million km. No insertion maneuver is needed to achieve this orbit. Orbits about L2 are dynamically unstable; small departures from equilibrium grow exponentially with a time constant of about 23 days. DWARFS will use its propulsion system to perform orbit maintenance maneuvers roughly once each month, totaling 4 m/s per year. Concerning the End of Life of the mission, the spacecraft will leave the vicinity of L2 via an unstable manifold, so there is no need for end of life maneuvers.



Sun-Earth L2 Libration point orbits have become extremely popular for many astrophysics missions due to the constant cold observation environment and low energy required for access. The Sun, Earth and Moon are intense sources of both straylight and thermal modulation, and reducing their effects drives the choice of orbit. Near Earth orbits are eliminated mainly because the large thermal influx renders it extremely difficult to reach temperatures below 100 K in the focal plane, or to achieve the required thermal stability. In an L2 orbit, both the Earth and the Sun are always on one side of the orbit. Thus half of the celestial sphere is always available for continuous observations at all times
The optimal choice of orbit, resulting from a trade-off of the various payload requirements, several spacecraft technical constraints (most importantly related to telecommunications to ground), and the transfer-to-orbit cost. We choose a quasi halo orbit, which has the advantage of having a 'free' transfer trajectory (the Halo Orbit Insertion HOI can be reduced to zero). Moreover we have a continuous communication with the Earth and also the solar panels can point toward the Sun at all times.

8.3 Operation center

The Mission Operations Centre (MOC) located at ESA's European Space Operations Centre (ESOC) in Darmstadt, Germany will be responsible for the daily operations, health and safety of the spacecraft. For communication with the spacecraft ESA's New Norcia (close to Perth, Australia) and Cebreros (close to Avila, Spain) deep space antennas will be used. The communication is provided via X-band for deep space communication technology, which assures a high data rate.

9 Budget, Management and Risk

System	TRL	Comment
Kick stage	7	LISA Pathfinder (launch 2012)
Launcher	9 (Ariane5 ICA) 6 (Ariane5 ICB) 9 (Soyuz)	
Sun shield	7	Smaller version of Herschel
Solar cell	8	
2-stage sterling cooler	8	Flight model on board of ACARI (launch 2006)
H^4 Joules Thomson cooler	7	Flight model developed for JEM/SMILES (launch 2009)
Instrument housing	7	Material space proved
Filter	8	
CCD	7	
Spectrometer	7	
Primary mirror	7	Similar mirror like Herschel

Power Consumption		
	Nominal	Peak
Service Module	68.3	148.3
Propulsion	0	10
Attitude Control	20	100
Communications	8,8	8,8
Command & Data Handling	19,5	19,5
Thermal	20	20
Payload	345	345
Instruments	<1mW	<1mW
Data Processing	25	25
Cooling	320	320
Power	1.2	1.2
Wiring	1,02	1,02
Total Power [W]	505.9	603.8

	Ariane5	Soyuz	Comments
Total mass [kg]	3000	1600	Mirrorsize 4m→3.5m
Launcher [M€]	50	50	Ariane5 shared with other passanger
Ground segment & Operation [M€]	75	70	
Spacecraft [M€]	725	500	
Payload [M€]	435	300	High cooling cost
Platform [M€]	290	200	
Total cost [M€]	**850**	**600**	

Figure 12: System

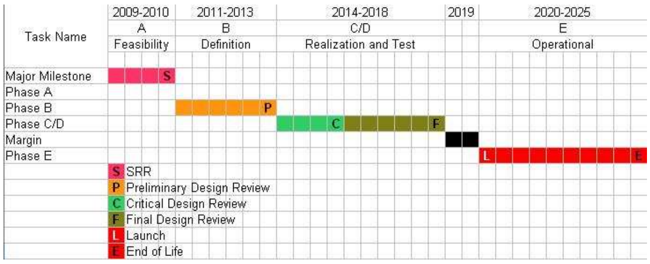


Figure 13: System

10 Descoping

Our main mission objectives and scientific requirements are satisfied by an Ariane 5 shared launch which bring the estimated total cost of the mission at around 850M Euro However, a descoping scenario has been studied with the use of a Soyouz-Fregat launcher. The diameter of the telescope goes down from 4m to 3.5 m and one out of two spectrometers is removed, as well as a the second cooler. In that scenario, the mass of the spacecraft goes down from 1800 kg to 1600 kg. The SNR of the signal goes also down by 11%, but the overall cost of the mission is reduced to 600 M Euro.

Reference Spacecraft -Space Mission Analysis and Design by Wiley J.Larson and James R.Wertz, 3rd edition

-Spacecraft Systems Engineering by Peter Fortescuel, John Stark and Graham Swinerd, 3rd edition

-Libration Point Orbits, Martin Hechler, ESOC 2009/4/3

-ESA Mission Herschel