# Introduction

Designing a space telescope is an incredibly complex job, with many requirements that must be met. Some of these are because of the scientific discoveries that the astronomers would like to make, while others are due to limits that the engineers put on the spacecraft. Beginning in the 1990s, astronomers and engineers around the world were busy designing the Herschel Space Observatory. This project will help you explore the kinds of decisions they had to make.

Your task is to design a space observatory for the UK Space Agency. You will have to make a number of decisions about what your space telescope will look like. If you are in a group, you could use a number of roles, but you will need to work together for a final solution:

## Rocket Engineer

The role of the engineer is to ensure that the mass and size of the structure does not surpass the limits of the launcher. The engineer must also select the appropriate launch site, and the orbit from which the satellite will observe.

## Project Manager

The role of the accountant is to ensure that the mission does not go over budget, and to ensure that the risk of overrunning in terms of budget is as low as possible.

## Instrument Scientist

The instrument scientist is in charge of making sure the instruments on-board are appropriate for meeting the science goals, and to ensure that they will be able to meet the scientific requirements.

## Mission Scientist

The mission scientist will ensure that the satellite's mirror and cooling system are suitable for the mission to succeed.

Once you have selected your mission, fill in the details on the draft proposal at the end of this document.

# Case Studies

Problems for groups (or individuals to solve) are (loosely) based on real life space observatory missions, from past, present and future.

1. A private organization has funded your group to research into the birth and evolution of stars the distant and nearby Universe. The budget of your mission is **£2 billion**. You will need the appropriate instruments on board your satellite in order to observe such objects.
2. A government research grant has come through to take images of the sky in ultraviolet, optical and near-IR wavelengths from a satellite in space, in order to map stars, galaxies and other yet to be discovered phenomena. The budget of your mission is **£800 million**.
3. A university has approached your group to design a mission for satellite telescope in order to analyse the spectra of interstellar dust in nearby galaxies. The budget of your mission is **£9 billion**. You will need the appropriate instruments on board the telescope in order to carry out the mission.
4. A private rocket company, SpaceX, has approached your group to launch a telescope into space in order to study the formation of planet. The resolution must be at least four times better than previous equivalent missions, and you must use their rocket. The budget for your mission is **£4 billion**.
5. A funding agency is providing funding to perform an all-sky survey from near infrared to far infrared. The budget of your mission is **£1.2 billion**.
6. Your group has received funding to send a telescope on board a satellite into space with the main objective of analysing stars in a nearby galaxy at very high resolution. The budget of your mission is **£10 billion**. Your group will need to use the appropriate instruments in order to collect data if it is to be analysed.
7. The government has asked you to design a satellite to take images of near-Earth asteroids. The mission should last for as long as possible. The European Space Agency will provide the launch and operations cost, also up to a total of **£700 million**, but only providing their launch site is used.

# Project Manager

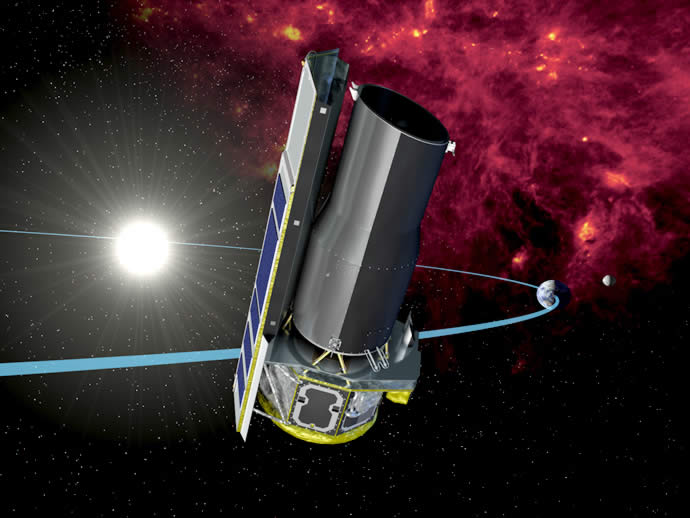
## Previous missions

Any satellite has to make scientific discoveries that are better than those that previous satellites have made. There have been a number of previous space telescopes launched to observe in a range of wavelengths, and some of the details are given below

|  |  |
| --- | --- |
| Infrared Astronomy Satellite (IRAS) | Infrared Space Observatory (ISO) |
| **Launched**: 1983  **Mission operators**: NASA  **Mission duration**: 10 months  **Instruments**: Mid-IR  **Operating Temperature:** 2 K  **Mirror diameter**: 0.7m  **Total satellite mass**: 800 kg  **Launch site**: Vandenberg Airforce Base, California, USA  **Launch vehicle**: Delta rocket  **Orbit**: Low-Earth orbit (900km altitude)  **Approximate cost**: £400 million | **Launched**: 1995  **Mission operators**: ESA  **Mission duration**: 2.5 years  **Instruments**: Near-IR, Mid-IR  **Operating Temperature**: 2K  **Mirror diameter**: 0.6m  **Satellite mass**: 2400kg  **Launch site**: Korou, French Guiana  **Launch vehicle**: Ariane 4  **Orbit**: High-Earth orbit (elliptical, ranging from 1000 – 70,000 km)  **Approximate cost**: £300 million |



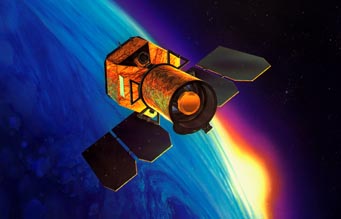
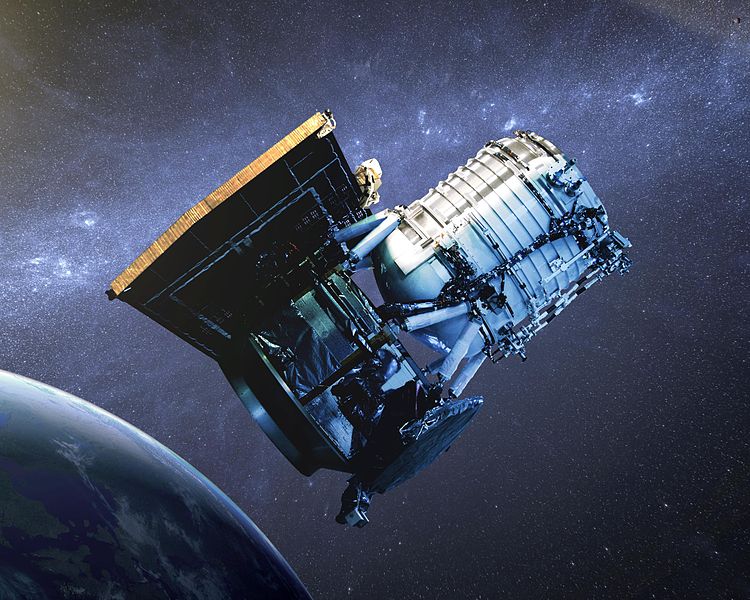
|  |  |
| --- | --- |
| Spitzer Space Telescope | Akari |
| **Launched**: 2003  **Mission operators**: NASA  **Mission duration**: 5.5 years\*  **Instruments**: Near-IR, Mid-IR  **Operating Temperature**: 5 K  **Mirror diameter**: 0.85m  **Satellite mass**: 860 kg  **Launch site**: Cape Canaveral, Florida, USA  **Launch vehicle**: Delta II rocket  **Orbit**: Earth-trailing orbit  **Approximate cost**: £800 million  **Notes**: \*Since further cooling is only required by the Mid-IR instruments, the Near-IR instruments continued to operate after the end of the nominal mission. | **Launched**: 2006  **Mission operators**: JAXA (Japan)  **Mission duration**: 1.5 years  **Instruments**: Near-IR, Mid-IR, Far-IR  **Operating Temperature**: 2 K  **Mirror diameter**: 0.7m  **Maximum resolution**: 44 arcseconds at 140 microns  **Satellite mass**: 950 kg  **Launch site**: Uchinoura Space Center, Japan  **Launch vehicle**: M-V rocket  **Orbit**: Low-Earth orbit (700 km altitude)  **Approximate cost**: £200 million (exc. launch cost) |



|  |  |
| --- | --- |
| Herschel Space Observatory | Hubble Space Telescope |
| **Launched**: 2009  **Mission operators**: ESA  **Mission duration**: 3.5 years  **Instruments**: Far-IR, Sub-mm  **Operating Temperature**: 0.3 K  **Mirror diameter**: 3.5m  **Satellite mass**: 4000 kg  **Launch site**: Korou, French Guiana  **Launch vehicle**: Ariane 5  **Orbit**: Earth-Sun L2 point  **Approximate cost**: £1 billion | **Launched**: 1990  **Mission operators**: NASA, ESA  **Mission duration**: >20 years  **Instruments**: Near-IR, Optical, UV  **Operating Temperature**: 300 K  **Mirror diameter**: 2.4m  **Satellite mass**: 11,000 kg  **Launch site**: Kennedy Space Centre  **Launch vehicle**: Space Shuttle Discovery  **Orbit**: Low-Earth orbit (600 km altitude)  **Approximate cost**: £2 billion |



|  |  |
| --- | --- |
| GALEX | WISE |
| **Launched**: 2003  **Mission operators**: NASA  **Mission duration**: 10 years  **Instruments**: UV  **Operating Temperature**: 300 K  **Mirror diameter**: 0.5m  **Satellite mass**: 280 kg  **Launch site**: Carrier Aircraft  **Launch vehicle**: Pegasus Rocket  **Orbit**: Low-Earth orbit (700 km altitude)  **Approximate cost**: £150 million (exc. launch cost) | **Launched**: 2010  **Mission operators**: NASA  **Mission duration**: 1 years  **Instruments**: Near-IR, Mid-IR  **Operating Temperature**: 300 K  **Mirror diameter**: 0.4m  **Satellite mass**: 400 kg  **Launch site**: Vandenberg  **Launch vehicle**: Delta II rocket  **Orbit**: Sun-synchronous orbit (500 km altitude)  **Approximate cost**: £300 million (exc. launch cost) |



## Satellite structure

Your colleagues are in the process of selecting various aspects of the mission design. Each of these will have an effect on the cost, size, and mass of the whole project. Your task is to keep track of the cost, and mass of all the components, and ensure that they meet the requirements.

Linking all of the other parts together is the main satellite structure. This structure sometimes referred to as the “service module” or “satellite bus” also carries the power, propulsion and communication systems. The cost, size and mass of this structure will primarily depend on the mirror selected by the mission scientist, as shown in the table below. A deployable mirror also requires a much more complex satellite structure, which will be **twice as expensive** and **twice as massive**. However, it will also be **half the diameter**.

|  |  |  |  |
| --- | --- | --- | --- |
| Mirror diameter | Structure diameter | Structure cost | Structure mass |
| **0.5 m** | 0.8 m | £100 million | 50 kg |
| **1 m** | 1.4 m | £200 million | 100 kg |
| **2 m** | 2.4 m | £500 million | 200 kg |
| **4 m** | 4.4 m | £1 billion | 300 kg |
| **8 m** | 10 m | £2 billion | 400 kg |



Mirror of the Herschel Space Telescope, during construction

## Mission budget and mass

### Satellite mass

Every part of the satellite has a mass. Use the table below to keep track of the mass of the satellite.

|  |  |
| --- | --- |
| Mass | |
| Satellite Structure: |  |
| Mirror: |  |
| Cooling System: |  |
| Instruments: |  |
| Total Satellite mass: |  |

Check with the Rocket Engineer that the satellite mass is compatible with the capability of the rocket.

### Budget

### Every part of the mission costs money. Use the table below to keep track of the total cost:

|  |  |
| --- | --- |
| Cost | |
| Satellite Structure: |  |
| Mirror: |  |
| Cooling System: |  |
| Instruments: |  |
| Development cost: |  |
| Launch cost: |  |
| Ground control cost: |  |
| Operations cost: |  |
| Total mission cost: |  |

# Mission Scientist

## Telescope Mirror

Telescopes work by focusing light using either lenses or mirrors, or sometimes a combination of the two. Mirrors tend to be much lighter and easier to manufacture, and so almost all space telescopes – and large ground-based telescopes - use them instead of lenses

The mirror of a telescope is one of the most important parts. It collects the light and focuses it onto the scientific instruments. Bigger mirrors are able to collect more light, and therefore see fainter objects more easily. They also have a higher resolution, and so can see finer detail.

The maximum possible resolution of a telescope is given by:

where ** is the wavelength of the light, *D* is the diameter of the telescope. The value of R is in radians. You can convert to other units using the following relations:

1 radian = degrees 1 degree = 60 arcminutes 1 arcminute = 60 arcseconds

This gives the maximum possible resolution that a telescope mirror can provide, and is called the “**diffraction limit**”. Note that it is different for different wavelengths. On previous satellites, not all instruments have taken advantage of this maximum resolution.

Example calculation using the Hubble Space Telescope

The Hubble Space Telescope has a main mirror that is 2.4m across, so . It observes optical light, which has a wavelength of around 600 nm, so . The resolution of the Hubble Space Telescope is:

### Your choices

The specifications of the selected mirror will affect the quality of the light collected by the telescope. Budget, mass and size constraints apply to these selections.

#### Diameter

A larger mirror will collect more light, however a smaller mirror will collect light at a faster rate. The size of the mirror is also a factor in the resolution of the detected light. The following formula describes the resolution of the telescope: where R is the resolution, is the wavelength of the observed light, and D is the diameter of the telescope.

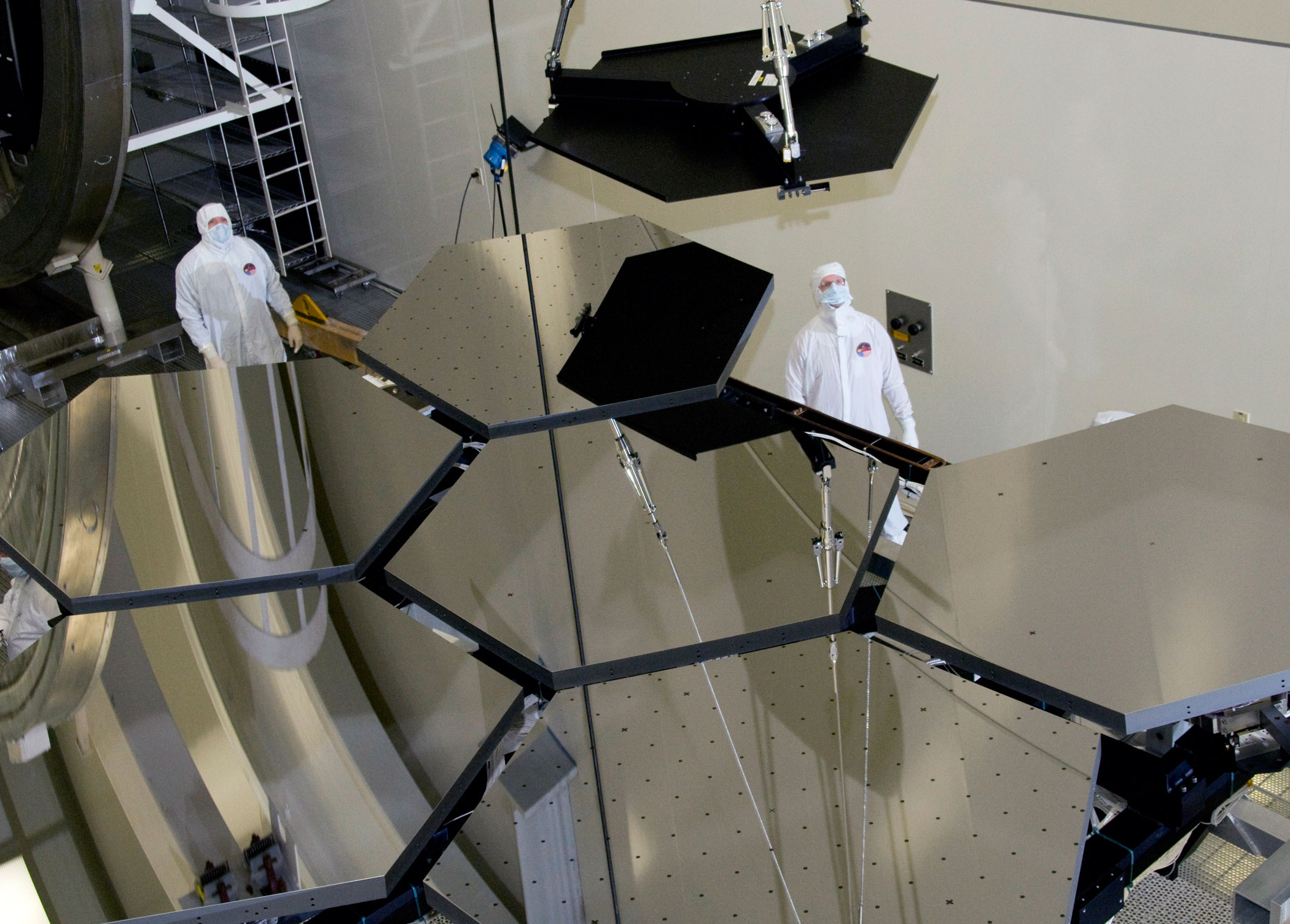
|  |  |  |
| --- | --- | --- |
| Mirror Diameter | Mass | Cost |
| 0.5 m | 3 kg | £12 million |
| 1 m | 10 kg | £25 million |
| 2 m | 30 kg | £50 million |
| 4 m | 100 kg | £200 million |
| 8 m | 300 kg | £1 billion |

#### Deployable

A deployable mirror will mean a smaller structure can be used to support the mirror, and also a smaller rocket. However, this does not mean a lighter structure, a deployable mirror will have **double the mass** and **4 times the cost** of a non-deployable mirror.

#### UV Quality

A mirror used for observing at ultraviolet wavelengths will need to be far more highly polished than a mirror used for longer wavelengths. As a result, a UV quality mirror is **twice as expensive to build**.

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## Cooling System

The Deployable mirror that will be aboard the James Webb Space Telescope, constructed from hexagonal segments

A cooling system may be required for your satellite, particularly for instruments observing longer wavelengths.

|  |  |
| --- | --- |
|  | Check with the Instrument Scientist what the temperature requirements of the instruments are |

### Your choices

You will need to choose the appropriate cooling temperature for the instruments on board the satellite; the temperature and their cost and mass are as follows

|  |  |  |
| --- | --- | --- |
| Temperature | Cost | Mass |
| **400 K** | £0 | 0kg |
| **300 K** | £500,000 | 20kg |
| **200 K** | £1 million | 40kg |
| **100 K** | £2.5 million | 70kg |
| **50 K** | £12 million | 150kg |
| **18 K** | £40 million | 500kg |
| **3K** | £90 million | 800kg |
| **0.3K** | £200 million | 1,200kg |



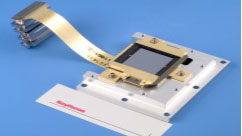
The cryogenic cooling system on-board the Herschel Space Telescope

# Instrument Scientist

## Instrument selection

The instruments on board the satellite will dictate the type of science that can be carried out by the telescope. Different wavelengths will observe different objects in the universe, as shown in the table below. The light from objects in the distant Universe is stretched by a phenomenon called redshift. This means that a given wavelength is sensitive to different objects in the nearby and distant Universe.

|  |  |  |  |
| --- | --- | --- | --- |
| Type | Wavelength | Our Galaxy and nearby galaxies | Distant Universe |
| Sub-mm | 300–1000 m | Birth of stars Very cold dust | Birth of stars Cool dust |
| Far-IR | 30–300 m | Cool dust  Birth of stars  Outermost regions of the solar system (Uranus, Neptune, Kuiper Belt, comets) | Birth of stars  Warm dust around young stars |
| Mid-IR | 3–30 m | Warm dust around young stars  Formation of planets  Inner Solar System (Mars, Jupiter, Saturn, Asteroids) | The first stars (100 million years after Big Bang) |
| Near-IR | 0.8 – 3 m | Cool stars (red dwarfs, red giants)  Near-Earth objects | The first galaxies in the Universe (400 million years after the Big Bang) |
| Optical | 0.4–0.8 m | Most Stars  Nearby galaxies | Hot, young stars |
| UV | 0.1–0.4 m | Hot, young stars | Very hot regions |

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An infrared detector chip

### Your choices

Some instruments need to operate at low temperatures. In general, the instrument must be cooler than the objects it is looking at. The temperature requirements of the different instruments are given below.

|  |  |
| --- | --- |
| Instrument wavelength | Temperature requirement |
| Sub-mm | 0.4 K |
| Far-infrared | 0.4 K |
| Mid-infrared | 40 K |
| Near-infrared | 4 K |
| Optical | 300 K |
| Ultraviolet | 400 K |

Check with the Mission Scientist that the cooling systems are adequate for the instruments you have chosen.

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The Andromeda galaxy, seen by the Herschel Space Observatory in the far-infrared

# Rocket Engineer

## Satellite orbit

The orbit selected will take into account many different factors. From an observing point of view, an appropriate Observing Fraction is needed. In terms of cost, a higher altitude will mean a more expensive Ground Control cost. Some orbits have additional requirements, such as a relay satellite or the ability to safely de-orbit the mission.

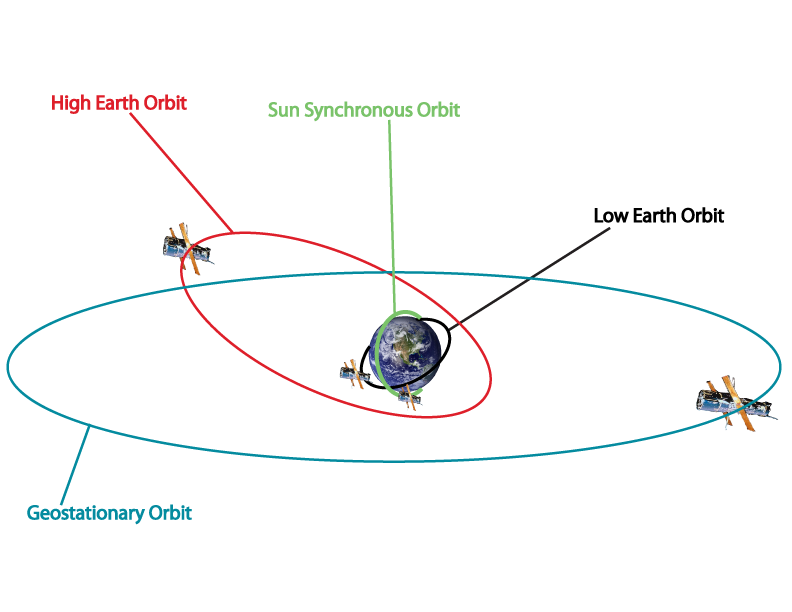
|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Orbit Selection | Orbit Altitude | Orbit Period | Observing Fraction | Ambient Temperature |
| Low Earth Orbit | <1000km | 90 minutes | 50% | 400K |
| Geostationary Orbit | 36,000km | 24 hours | 50% | 300K |
| Earth-Sun L2 | 1,500,000 km | 365 days | 100% | 300K |

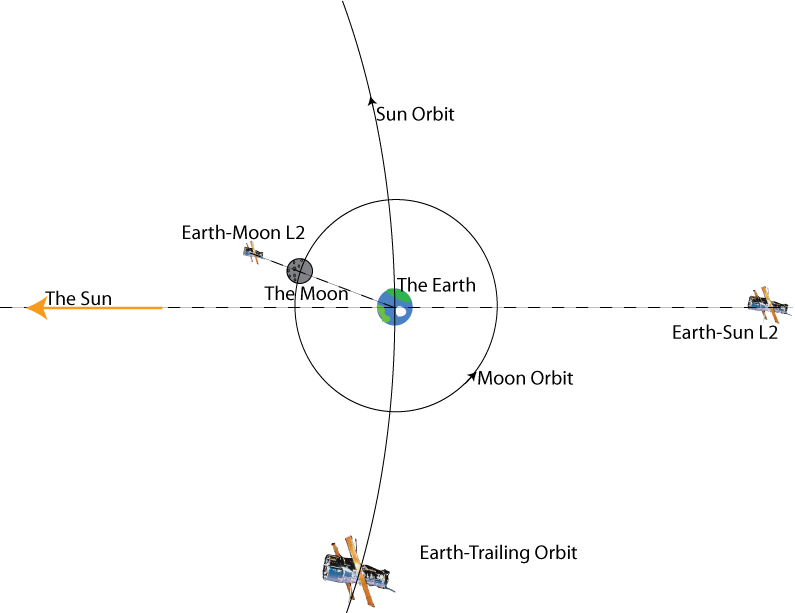
The period of an orbit depends on the mass of the body it is orbiting and the distance from its centre.

The gravitational pull from the central object is given by Newton’s law of gravity:

Where G is Newton’s gravitational constant (6.67x10–11 N m2 kg-2), M is the mass of the central object (e.g. the Earth, m is the mass of the orbiting object (e.g. the satellite), and r is the distance from the centre of each.

Assuming the orbit is circular, this gravitational force acts as a centripetal force, which is related to the velocity, *v*, of the orbiting object by:



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Schematic diagrams of the available orbit selections

Schematic diagrams of the available orbit selections

### Your Choices

#### Low Earth-orbit

These are satellites in orbit around the Earth, typically less than 1000 km above the surface and with an orbital period of 90-100 minutes. To reduce space debris in the future, a satellite in low-Earth orbit must be fitted with the ability to de-orbit safely at the end of the mission, which **increases the launch cost by 20%**. For half of each orbit, the satellite is between the Earth and the Sun, and so **can only observe for around 50% of the time**. The small amount of drag from the Earth’s atmosphere **means that the fuel lifetime is 10 years**. This orbit is suitable for **all types of cooling systems**, though the proximity of the Earth **reduces the cryogenic lifetime by 30%.** Ground control costs are **£20 million per year**.

#### Geostationary orbit

A satellite in geostationary orbit remains above the same place on the Earth’s surface at all times, since it orbits roughly once every 24 hours. This requires it to be at an altitude of around 36,000 km. Since it spends half its time between the Earth and the Sun a satellite in geostationary orbit can typically **only observe for around 50% of the time**. Since the satellite is in a high orbit **the fuel lifetime is 20 years**. Ground control costs are **£40 million per year**.

#### Earth-Sun L2 point.

The “L2” point of the Earth-Sun system is the position at which a satellite with orbit the Sun at the same rate as the Earth, despite being 1.5 million km further away. This is because of the slight increase in centripetal force due to the Earth’s gravitational pull. Since the Earth and the Sun are constantly in the same direction, the satellite **can observe 100% of the time**. Relatively large amounts of fuel are required to maintain orbit at an L2 point, so **the fuel lifetime is 10 years**. Ground control costs are **£50 million per year**.

## Operational lifetime

The operational lifetime of the mission will add to the cost required to run the satellite. It may be limited by the fuel or coolant supply.

Check with the Mission Scientist that the coolant will meet the lifetime requirements



Check with the Project Manager that the mission lifetime does not exceed the fuel lifetime

Check with the Mission Scientist that the orbit is suitable for the cooling systems chosen.

## Launch Vehicle

There are numerous launch vehicles and launch sites to use for your satellite from. However, different launch vehicles are launched form different sites, and the two must be compatible.

Different launchers have different sizes and have different limits in terms of the mass they can carry. The mass carried depends the on the orbit chosen. It is advisable for the satellite mass to below 80% of maximum mass for the chosen launch vehicle. The maximum mass is lower for launches beyond low Earth orbit, and some launches are not able to achieve particular orbits. Some operators are a little more efficient than others in terms of cost in order to launch satellites, and other launchers.

### Your choices

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Launch vehicle | Diameter | Maximum mass to LEO | Maximum mass beyond LEO | Launch cost | Operator |
| Ariane 5 | 5.5 m | 20 t | 9 t | £100 million | ESA (Europe) |
| Soyuz | 3 m | 8 t | 4 t | £60 million | Roscosmos (Russia) |
| Delta IV | 5 m | 23 t | 13 t | £200 million | NASA (USA) |
| H-2B | 5 m | 15 t | 8 t | £80 million | JAXA (Japan) |
| Vega | 3 m | 2.3 t | -- | £23 million | ESA (Europe) |
| Pegasus | 1.2 m | 0.4 t | -- | £15 million | Orbital (USA) |
| Falcon 9 | 3.5 m | 10 t | 7 t | £40 million | SpaceX (USA) |



Check with the Project Manager that the satellite mass and the rocket capacity are compatible.



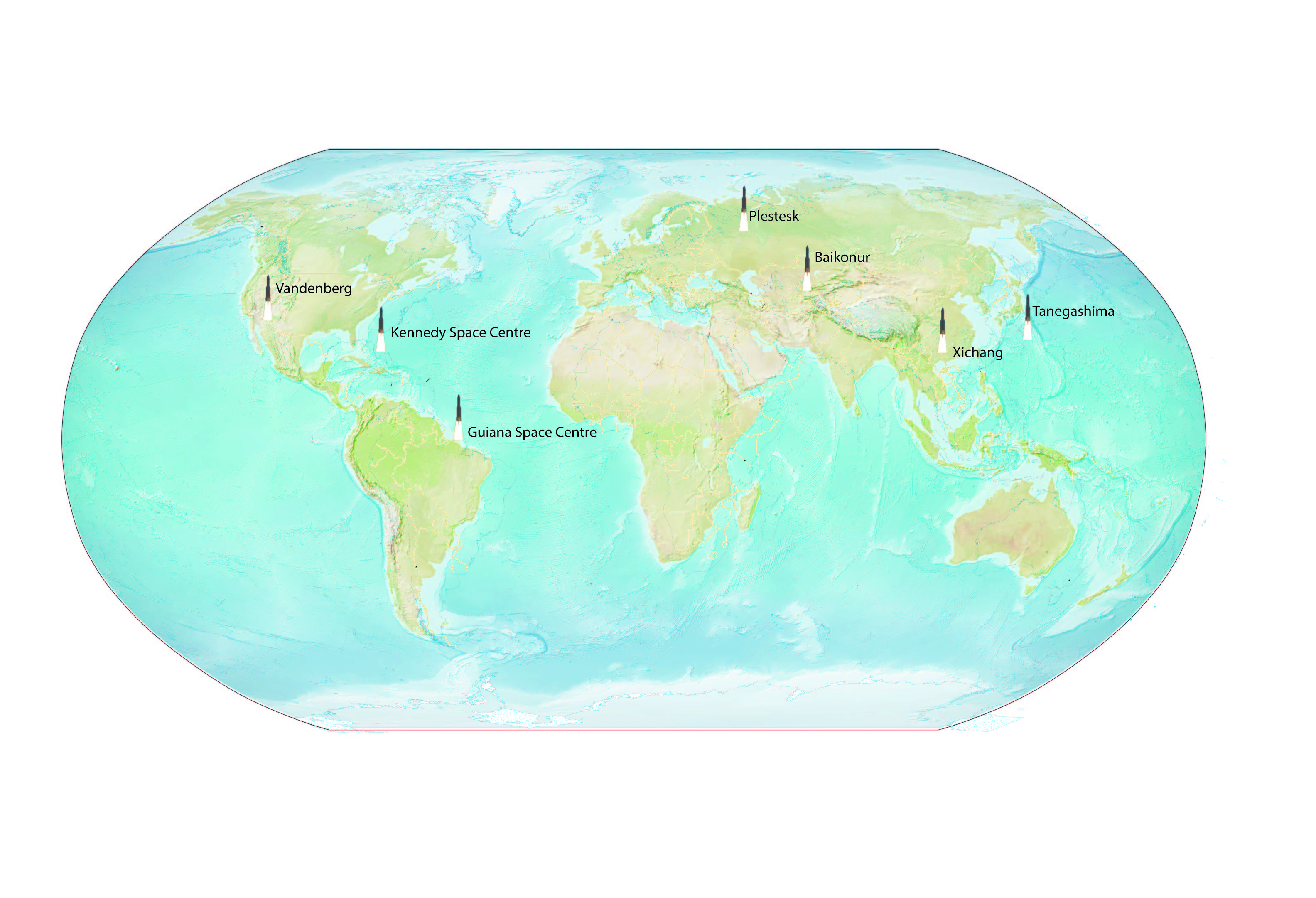
Ariane 5 Delta IV H-2B Proton-M

## Launch Site

Different sites also effect the type of Orbit available, asss a rocket cannot be launched and immediately fly over a highly populated regions. To reach orbits beyond low-Earth orbit, a rocket must be launched in the direction of the Earth’s rotation.

### Your Choices

|  |  |  |
| --- | --- | --- |
| Launch site | Launch trajectories | Launch vehicles supported |
| Guiana Space Centre, French Guiana | North, East | Ariane 5, Soyuz, Vega |
| Baikonur, Russia | North, East | Soyuz, Proton-M |
| Kennedy Space Centre, Florida | East | Delta II, Delta IV, Atlas V, Falcon 9 |
| Tanegashima, Japan | South, East | H-2B |
| Carrier Aircraft | Any | Pegasus |



Locations of Launch sites around the world

# Example Proposal Letter

Dear \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_,

We would like to propose a project to send a telescope into space on board a telescope. The aim of the mission is to \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_.

Previous similar missions are\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_. This mission will advance on these by \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

## Instruments

The instruments on board will be \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ . They will allow the science goals to be met by

## Mirror

The main mirror of the telescope will be \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ . This will allow the instruments to achieve resolutions from \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ to \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ .

## Cooling System

The minimum operating temperature required by the instruments is \_\_\_\_\_\_\_\_\_\_ Kelvin. The temperature on board the satellite will be \_\_\_\_\_\_\_\_\_\_\_\_\_\_.

## Mass budget

The total mass of the satellite will be \_\_\_\_\_\_\_\_\_\_\_\_ . The breakdown from the individual components is given below

|  |  |
| --- | --- |
| Mass budget | |
| Satellite Structure: |  |
| Mirror: |  |
| Cooling System: |  |
| Instruments: |  |
| Total Satellite mass: |  |

## Orbit Selection

The satellite will observe from \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ , at a distance of \_\_\_\_\_\_\_\_\_\_\_\_ from Earth. The orbital period will be \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ , and the maximum fuel lifetime for maintaining such an orbit is \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_. The mission duration will be \_\_\_\_\_\_\_\_\_\_\_\_\_\_ years

## Launch vehicle and site

To reach orbit, the satellite will be launched on a \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ , operated by \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ , from \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ . The maximum capacity of this launch vehicle is \_\_\_\_\_\_\_\_\_\_ ,

## Budget

The total cost of the mission will be \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ .

|  |  |
| --- | --- |
| Cost | |
| Satellite Structure: |  |
| Mirror: |  |
| Cooling System: |  |
| Instruments: |  |
| Development cost: |  |
| Launch cost: |  |
| Ground control cost: |  |
| Operations cost: |  |
| Total mission cost: |  |

Kind Regards,

\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_