

Design a Space Telescope

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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.

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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.

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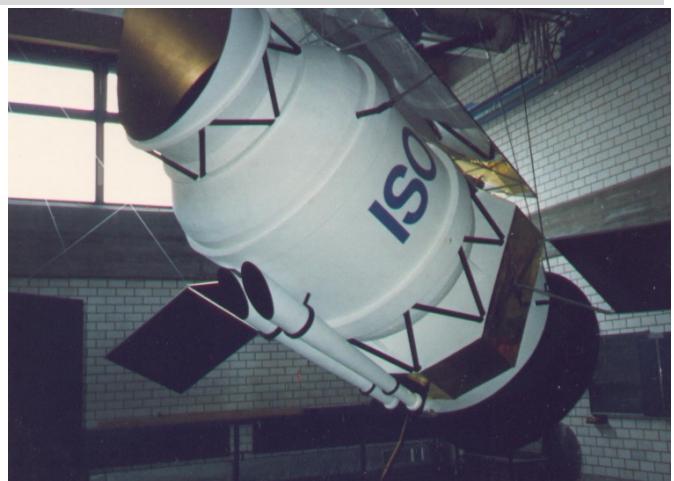
Project Manager



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

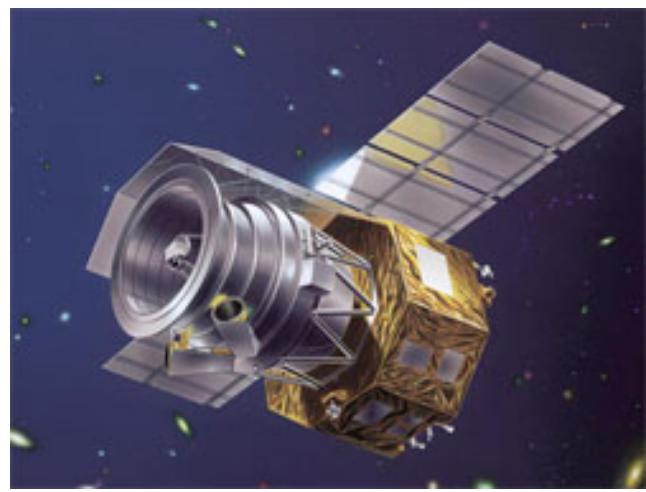
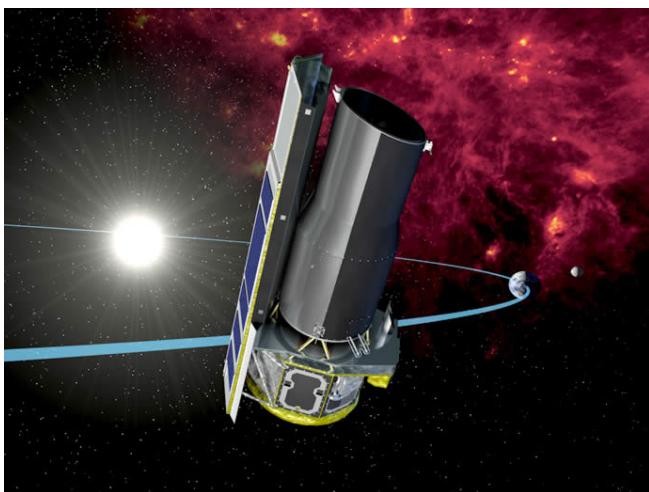
Infrared Astronomy Satellite (IRAS)	Infrared Space Observatory (ISO)
Launched: 1983	Launched: 1995
Mission operators: NASA	Mission operators: ESA
Mission duration: 10 months	Mission duration: 2.5 years
Instruments: Mid-IR	Instruments: Near-IR, Mid-IR
Operating Temperature: 2 K	Operating Temperature: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



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



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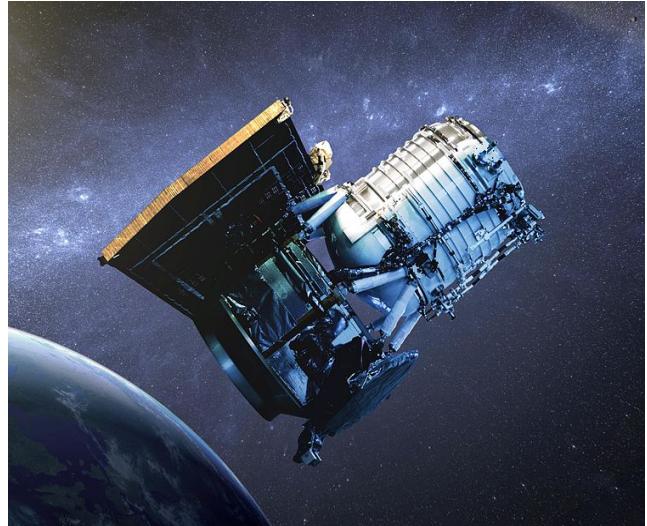
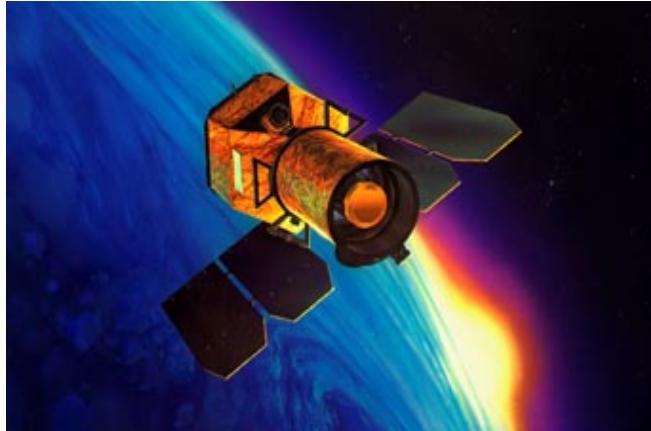
Herschel Space Observatory	Hubble Space Telescope
Launched: 2009	Launched: 1990
Mission operators: ESA	Mission operators: NASA, ESA
Mission duration: 3.5 years	Mission duration: >20 years
Instruments: Far-IR, Sub-mm	Instruments: Near-IR, Optical, UV
Operating Temperature: 0.3 K	Operating Temperature: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



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



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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

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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:	

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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:

$$R \approx 1.22 \frac{\lambda}{D}$$

where λ 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:

$$1 \text{ radian} = 180/\pi \text{ degrees} \quad 1 \text{ degree} = 60 \text{ arcminutes} \quad 1 \text{ arcminute} = 60 \text{ arcseconds}$$

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 $D = 2.4 \text{ m}$. It observes optical light, which has a wavelength of around 600 nm, so $\lambda = 600 \text{ nm} = 6 \times 10^{-7} \text{ m}$. The resolution of the Hubble Space Telescope is:

$$R \approx 1.22 \frac{\lambda}{D}$$
$$1.22 \frac{6 \times 10^{-7}}{2.4} \quad 3.05 \times 10^{-7} \text{ radians}$$
$$0.06 \text{ arcseconds.}$$

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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, λ is the wavelength of the observed light, and D is the diameter of the telescope.

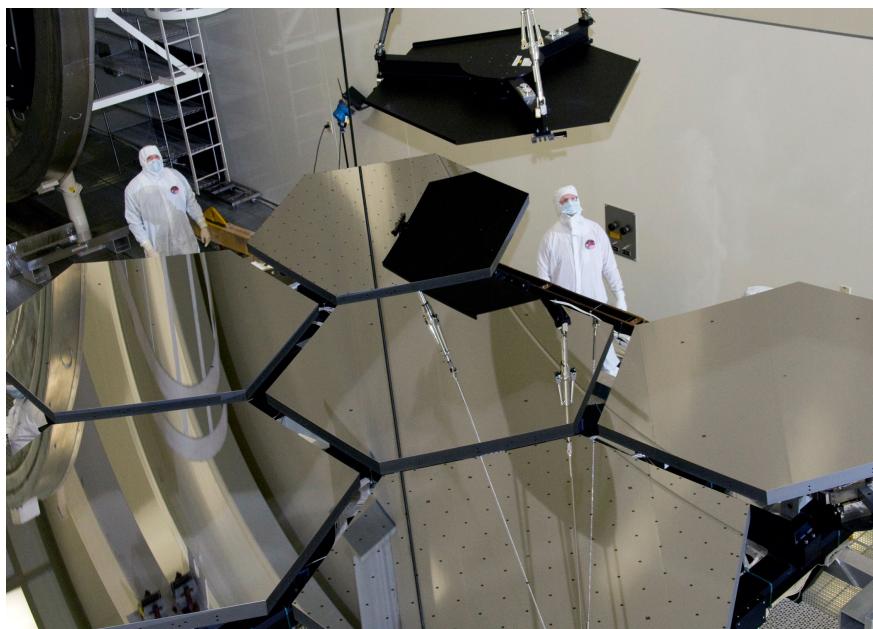
Mirror Diameter	Mass	Cost
0.5 m	3 kg	£12 million
1 m	10 kg	£25 million
2 m	30 kg	£50 million
4 m	100 kg	£200 million
8 m	300 kg	£1 billion

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**.



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

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Cooling System

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

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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 μm	Birth of stars Very cold dust	Birth of stars Cool dust
Far-IR	30–300 μm	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 μm	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 μm	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 μm	Most Stars Nearby galaxies	Hot, young stars
UV	0.1–0.4 μm	Hot, young stars	Very hot regions



An infrared detector chip

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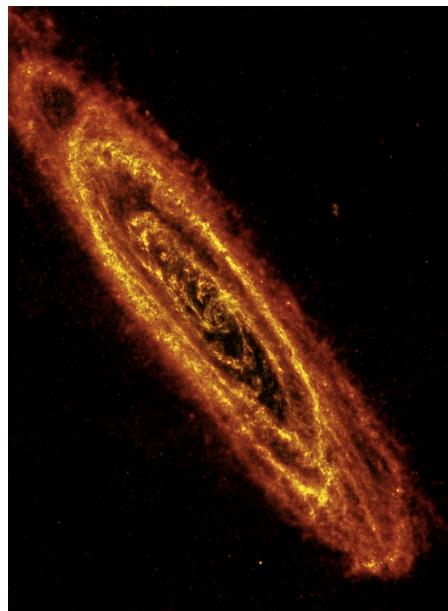
Your choices

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.



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

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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:

$$F = \frac{GMm}{r^2}$$

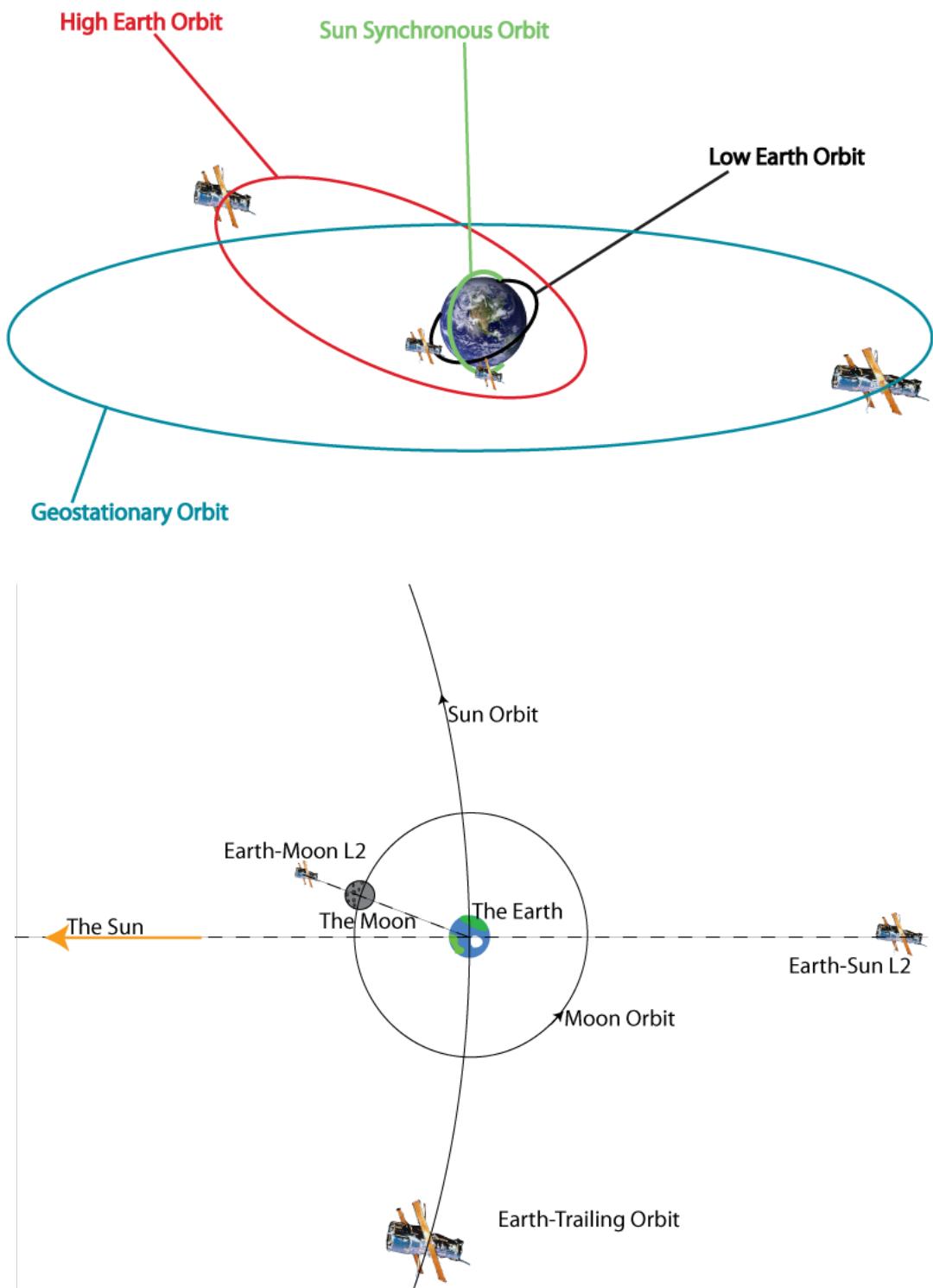
Where G is Newton's gravitational constant ($6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$), M is the mass of the central object (e.g. the Earth, m is the mass of the orbiting object (e.g. the satellite), and r is the distance from the centre of each.

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:

$$F = \frac{mv^2}{r}$$

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Schematic diagrams of the available orbit selections

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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 orbits 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.

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Launch Vehicle

There are numerous launch vehicles and launch sites to use for your satellite from. However, different launch vehicles are launched from 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 on the orbit chosen. It is advisable for the satellite mass to be 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

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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

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Locations of Launch sites around the world

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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 _____.

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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 _____ ,

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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,
