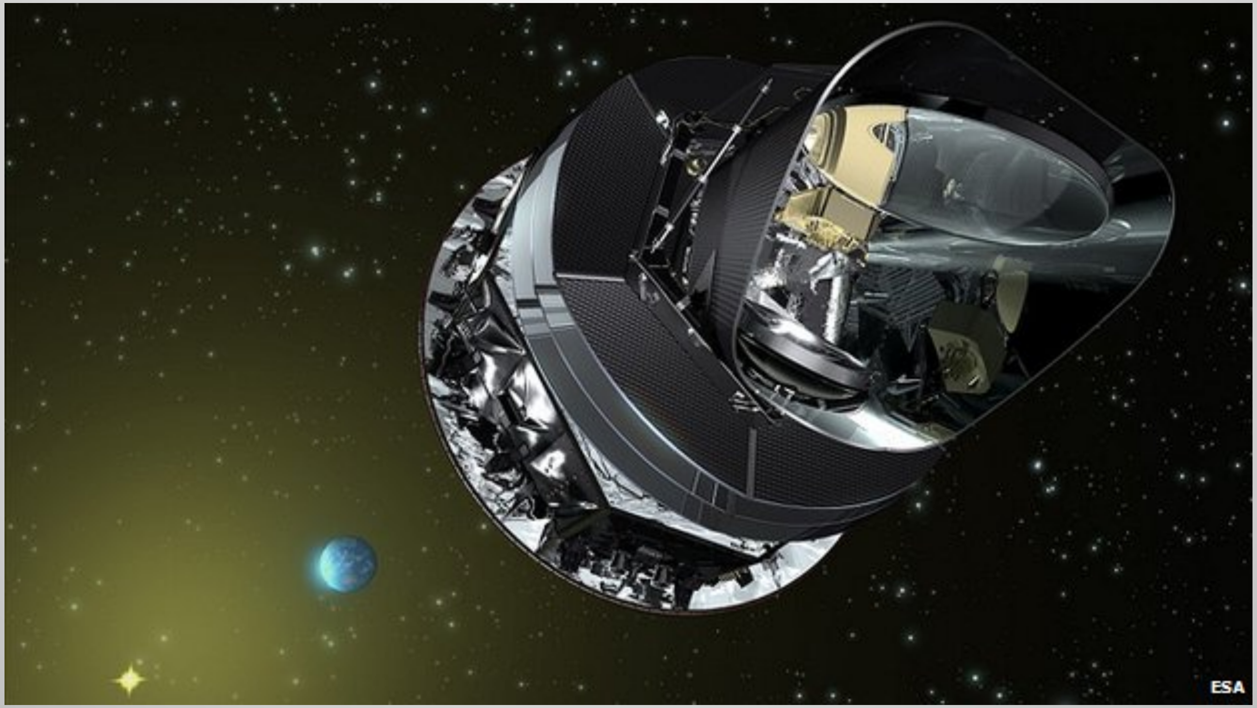
Designing a Space Telescope
KS5



Guide to this presentation

White slides are section headings, and are hidden from the presentation. Show or hide slides that match the way you believe the presentation should be given, for example, whether to present individual questions or case studies during presentation, or just present them in work sheets during activity.

Introduction

Basic start to the presentation

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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 the 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

Roles and Task

- The roles the students may want to consider distributing within the group.
- Case studies describing what the groups need to achieve.
- Questions for individuals to answer, respective of their role within the group.

Roles Within The Groups

Rocket Engineer

- Ensures that the mass and size of the structure does not surpass the limits of the launcher
- Select the appropriate launch site, and the orbit from which the satellite will observe

Project Manager

- Ensure that the mission does not go over budget.
- Ensure that the risk of overrunning in terms of time or budget is as low as possible.

Instrument Scientist

- Makes sure the instruments on-board are appropriate for meeting the science goals.
- Ensures that instruments will be able to meet scientific requirements.

Mission Scientist

- Ensures that the satellite's mirror will be suitable for the mission to succeed.
- Ensures that the satellite's cooling system will be suitable for the mission to succeed.

Case Studies

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1. A private organization has funded your group to research into the birth and evolution of stars the distant and nearby Universe, with full analysis of the spectra of the event. 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, visible and nearby 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 **£400 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 planets and their chemical composition. 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 billion**. The satellite should launch within 10 years.
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. You should aim to capture both the spectra and image data. The budget of your mission is **£15 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, but the **£700 million** funding for the development of the satellite will expire in eight years. 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.

Individual Questions

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Project Manager Questions:

1. What factors made the Hubble telescope so expensive to launch and maintain?
2. What factors made the Akari telescope so much cheaper than Hubble to launch and maintain?
3. What is the dominant factor in the cost of a satellite mission?

Rocket Engineer Questions:

1. A satellite in low Earth orbit is typically 300 km above the surface. Use the equations above to calculate its speed
2. Use the two equations above to show that the relationship between the period and radius of a satellite's orbit around the Earth is given by the following equation
3. What altitude would a geostationary satellite orbit at?
4. Calculate the velocity of the Earth's surface at the equator as it spins on its axis. Is this faster or slower than a satellite in low-Earth orbit?
5. In which direction does the Earth's surface move as it rotates?

Mission Scientist Questions:

1. Calculate the resolution of the Lovell Telescope at Jodrell Bank. The main dish is 76 m across, and it typically works at a wavelength of around 21 cm.
2. How does that compare to the Hubble Space Telescope?
3. If a telescope were to have the same resolution as the Hubble Space Telescope, but observe wavelengths of 100 microns, what diameter mirror would it need? [1 micron = 1 millionth of a metre]

Instrument Scientist Questions:

1. Convert the following temperatures from degrees Celsius to Kelvin:
   a) 20°C, b) 75°C, c) –50°C
2. Using Wein's displacement law, do colder objects typically emit at longer or shorter wavelengths.
3. Given the temperature of the following 3 objects, calculate the wavelength at which they are brightest using Wien's law: a) A Person (37°C), b) Jupiter (160K), c) a hot young star (10,000°C)
4. The light from very distant objects is stretched to longer wavelengths. Does this make them appear warmer or cooler?

Previous Missions

A taster for students to know what has been before

Previous Missions

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Infrared Astronomy Satellite (IRAS)

Launched: 1983
Mission operators: NASA
Mission duration: 10 months
Instruments: Mid-IR (Camera), Mid-IR (Spectrometer)
Cooling: Passive + Cryogenic
Operating Temperature: 2 K
Coolant: 600 litres liquid helium
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

Infrared Space Observatory (ISO)

Launched: 1995
Mission operators: ESA
Mission duration: 2.5 years
Instruments: Near-IR (Camera), Mid-IR (Camera) Mid-IR (Spectrometer)
Cooling: Passive & Cryogenic
Operating Temperature: 2K
Coolant: 2300 litres of liquid helium
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

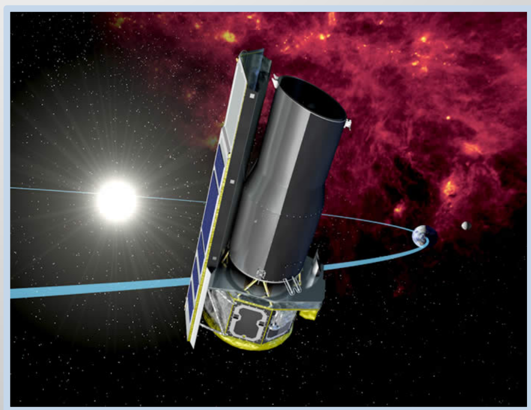
Spitzer Space Telescope

Launched: 2003
Mission operators: NASA
Mission duration: 5.5 years*
Instruments: Near-IR (Camera), Mid-IR (Spectrometer), Mid-IR (Camera)
Cooling: Passive & Cryogenic
Operating Temperature: 5 K
Coolant: 340 litres of liquid helium
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 the cryogenic cooling is only required by the Mid-IR instruments, the Near-IR instruments continued to operate after the end of the nominal mission.

Akari

Launched: 2006
Mission operators: JAXA (Japan)
Mission duration: 1.5 years
Instruments: Near-IR (Camera), Mid-IR (Camera), Far-IR (Camera)
Cooling: Passive & Cryogenic
Operating Temperature: 2 K
Coolant: 170 litres of liquid helium
Mirror diameter: 0.7m
Maximum resolution: 44 arc seconds 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)



Previous Missions

Herschel Space Observatory

Launched: 2009
Mission operators: ESA
Mission duration: 3.5 years
Instuments: Far-IR (Camera & Spectrometer), Sub-mm (Camera & Spectrometer), Far-IR & Sub-mm (Spectrometer)
Cooling: Passive & Cryogenic & Active
Operating Temperature: 0.3 K
Coolant: 2300 litres of liquid helium
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

Hubble Space Telescope

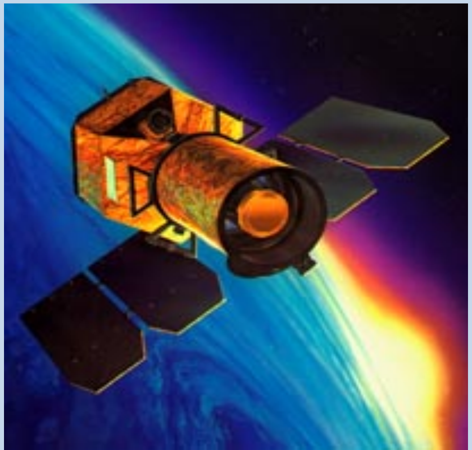
Launched: 1990
Mission operators: NASA, ESA
Mission duration: >20 years
Instruments: Near-IR (Camera & Spectrometer), Optical (Camera), UV
(Spectrometer), Optical (Camera & Spectrometer)
Cooling: Passive
Operating Temperature: 300 K
Mirror diameter: 2.4m
Satellite mass: 11,000 kg
Launch site: Kennedy Space Centre
Launch vehicle: Space Shuttle Discovery
Orbit: Low-Earth orbit (600 km altitude)
Approximate cost: £2 billion

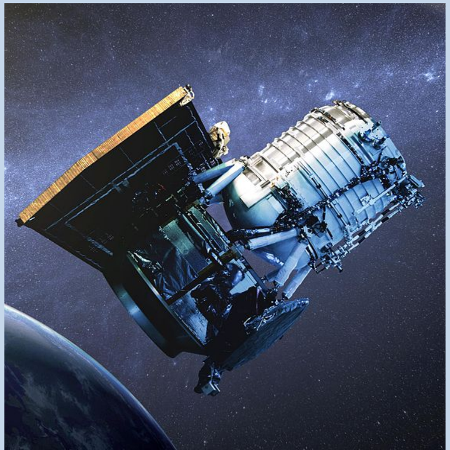
GALEX

Launched: 2003
Mission operators: NASA
Mission duration: 10 years
Instruments: UV (Camera)
Cooling: Passive
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)

WISE

Launched: 2010
Mission operators: NASA
Mission duration: 1 years
Instruments: Near-IR (Camera), Mid-IR (Camera)
Cooling: Passive
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)





Parameters

A small guide to the variables to be selected by the group, including mirror diameter, cooling system, instruments, orbit, launch vehicle, and launch site.

Satellite Structure

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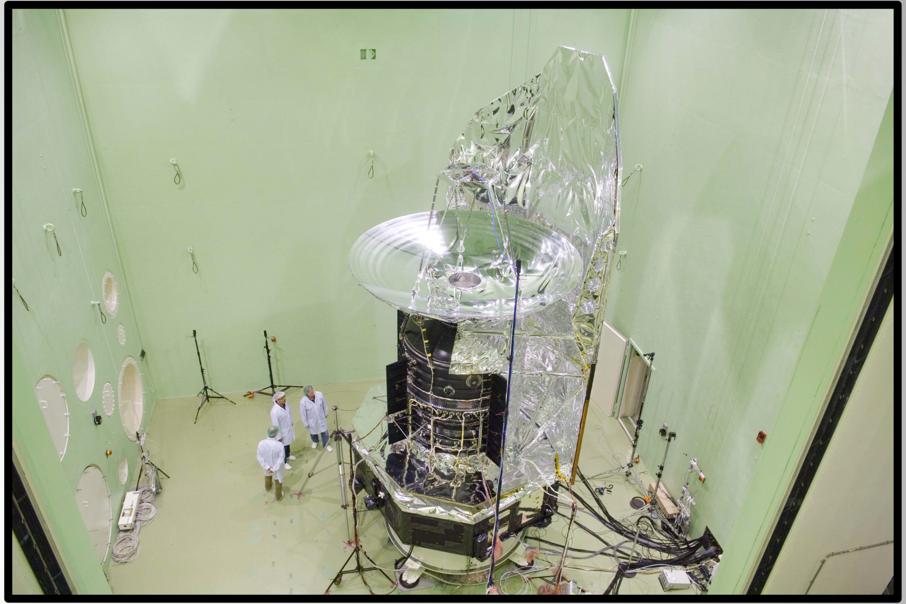
- The structure holds everything together, sometimes referred to as the "service module" or "satellite bus", it also carries the power, propulsion and communication systems.
- The cost, size and mass of this structure will primarily depend on the mirror selected by the mission scientist, as shown in the table below.
- **The development time of the satellite structure is 5 years.**
- 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**.



Structure of Herschel undergoing acoustic tests

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

Telescope Mirror

The parameters selected for your mirror will effect the quality of the data collected. Your parameters to select are:

- **Diameter** – Diameter effects the resolution of the telescope, which can be calculated from this equation: $R \approx 1.22\frac{\lambda}{D}$
- **Deployable** – A deployable mirror will mean a smaller structure can be used to carry the mirror, however this does come at a cost in both money and mass
- **UV Quality** – A mirror used for observing in UV will require much better quality than in IR due to the higher resolution.

Mirror used by the Herschel Space Observatory

Cooling System

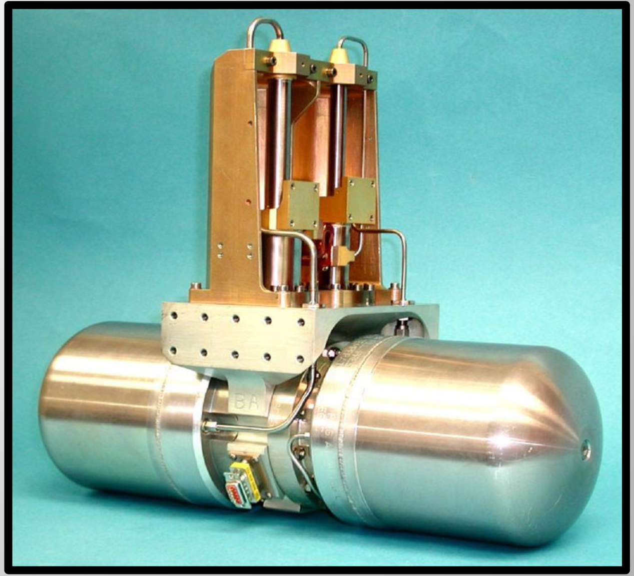
Some Instruments will require very low temperatures in order to operate. Here are your choices in how to cool the telescope:

- **Passive** – Most basic method of cooling
- **Cryogeni**c- Super-cold liquids and gases are used to cool the instruments, more expensive than Passive cooling. Each 2 years of lifetime requires more cryogenic liquid, which will add mass.

Lifetime	Cost	Mass
2 years	£20 million	500kg
4 years	£50 million	1,000kg
8 years	£250 million	2,000kg

- **Active** – The most complex of all the methods. May seem expensive in the short run, but in the long run is cost effective and light in comparison to Cryogenic cooling

Cooling system aboard Herschel



Cooling system aboard the James Webb Space Telescope

Instrument Selection

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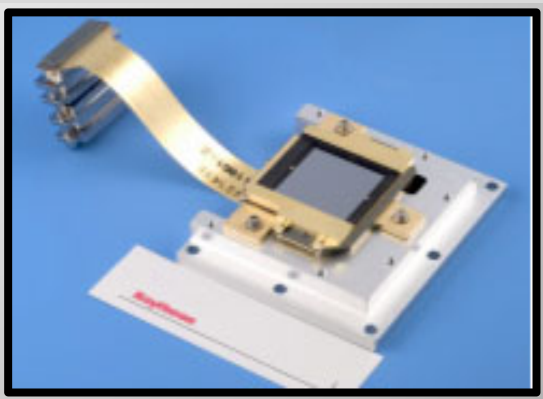
Type	Wavelength	Our Galaxy and nearby galaxies	Distant Universe
Sub-mm	300–1000 μm	Birth of stars Very cold dust	Birth of stars Cool dust
Far-IR	30–300 μm	Cool dust Birth of stars Outermost regions of the solar system (Uranus, Neptune, Kuiper Belt, comets)	Birth of stars Warm dust around young stars
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

Different things can be observed at different wavelengths. You will need to pick appropriate instruments to conduct the correct science, including instrument wavelength, and type. Here are your choices.

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

Instrument type	Mass	Cost	Development time
Camera	50 kg	£50 million	0.5 years
Spectrometer	50 kg	£50 million	0.5 years
Both	75 kg	£75 million	1 year

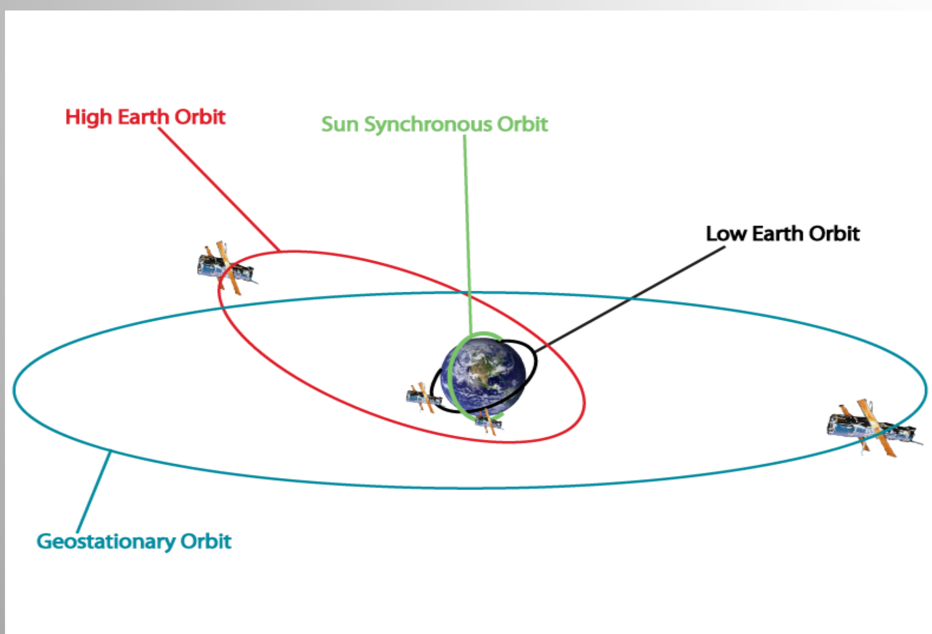


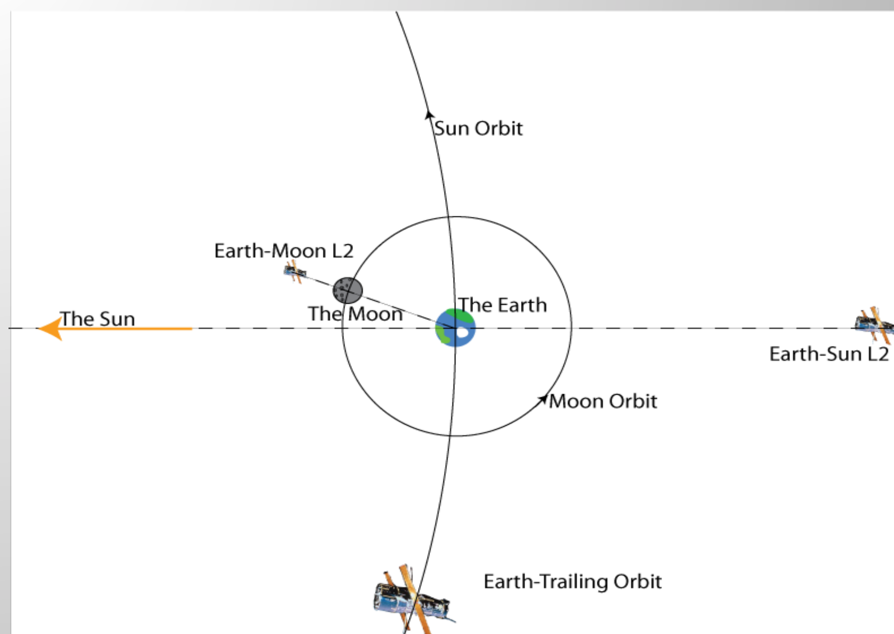
IR Detector

Satellite Orbit

Once in space, there are different orbital paths the satellite can take. Different orbits will allow for better seeing. It is also worth noting, that particular cooling systems won't work in lower altitude orbits. Here are your options.

Orbit Selection	Orbit Altitude	Orbit Period	Observing Fraction	Ambient Temperature
Low Earth Orbit	<1000km	90 minutes	50%	400K
High Earth Orbit	>1000km	100 minutes	50%	300K
Sun-Synchronous Orbit	<1000km	90 minutes	100%	400K
Geostationary Orbit	36,000km	24 hours	50%	300K
Earth-Trailing	10,000,000 km	370 days	100%	300K
Earth-Moon L2	400,000 km	27 days	50%	300K
Earth-Sun L2	1,500,000 km	365 days	100%	300K





Launch Vehicle

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Available to your mission will be a number of launch vehicles in order to get your satellite into space. Different vehicles are provided by different organisations, in different countries. Different vehicles will allow you to carry larger, heavier structures, into more ambitious orbits, but these will cost extra.

Launch vehicle	Diameter	Maximum mass to LEO	Maximum mass beyond LEO	Launch cost	Operator	Success Rate
Ariane 5	5.5 m	20 t	9 t	£100 million	ESA (Europe)	96 %
Soyuz	3 m	8 t	4 t	£60 million	Roscosmos (Russia)	98 %
Delta II	3 m	6 t	2 t	£30 million	NASA (USA)	99 %
Delta IV	5 m	23 t	13 t	£200 million	NASA (USA)	95 %
Proton-M	4 m	20 t	5 t	£60 million	Roscosmos (Russia)	88 %
H-2B	5 m	15 t	8 t	£80 million	JAXA (Japan)	95 %
Vega	3 m	2.3 t	--	£23 million	ESA (Europe)	98 %
Pegasus	1.2 m	0.4 t	--	£15 million	Orbital (USA)	92 %
Long March 3B	3.5 m	12 t	5 t	£30 million	CNSA (China)	75 %
Atlas V	3.5 m	19 t	9 t	£150 million	NASA (USA)	98 %
Falcon 9	3.5 m	10 t	7 t	£40 million	SpaceX (USA)	97 %

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Ariane 5

Soyuz

Delta II

Delta IV

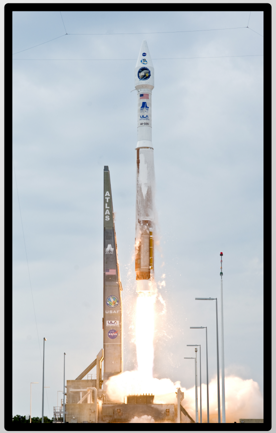
Proton M

Pegasus

H-2B

Vega

Long March 3B



Atlas V

Falcon 9

Launch Site

Different organisations have different locations from which a satellite can be launched from. Bare in mind that the site and vehicle have to be compatible, for instance a Russian rocket cannot be launched from Xichang, a Chinese launch site. Another thing to consider is that launch sites can only launch into particular trajectories.

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
Plestesk, Russia	North	Soyuz, Proton-M
Kennedy Space Centre, Florida	East	Delta II, Delta IV, Atlas V, Falcon 9
Vandenberg, California	North	Delta II, Delta IV, Atlas V, Falcon 9
Xichang, China	North, East	Long March 3B
Tanegashima, Japan	South, East	H-2B
Carrier Aircraft	Any	Pegasus

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Map containing locations of launch sites