The orbits of the space telescopes Herschel and Planck

How to reach libration point L₂ and the advantages it offers to astronomic observation

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The two European satellites Herschel and Planck are each dedicated to studying totally different astronomic questions. But a single Ariane 5 rocket will carry them into space together. They will fulfill their mission in a place far beyond the Moon in the opposite direction to the Sun. The orbital aspects of this project and the resulting advantages for science are the topic of this article.

In May 2009 an Ariane 5 will be sending the Herschel and Planck space telescopes on their journey to libration point L₂ in the Sun-Earth system. This ‘equilibrium point’ is located around 1.5 million kilometres outside of the Earth’s orbit on an extension of the line that connects the Sun and the Earth. Seen from L₂ the Sun and the Earth always lie in the same direction. A telescope positioned here can therefore be relatively easily shielded from infrared radiation coming from the Sun and the Earth and its line of vision is not additionally restricted by the Earth and Moon. Due to these geometric advantages over the next few years a whole fleet of astronomy satellites will populate the region around L₂. At libration point L₂ an equilibrium of gravitational and centrifugal forces prevails in the system that rotates with the Earth around the Sun - in an ideal case a satellite parked there remains there. However, this equilibrium is unstable. The problem of sending a space vehicle to L₂ and holding it there is comparable to the problem of sending a mini-golf ball to the top of a slippery hill in such a way that it will remain there. Just how the Herschel and Planck satellites are expected to deal with this problem in order to accomplish their astronomic missions will be described in this article.

Astronomy in space
In the past, the observation of the planets using earth-bound telescopes was an important part of astronomy. Exploration using automatic or remote-controlled probes, or even by astronauts on-site, means that earth-bound astronomic observations of all of the bodies in the Solar System is less interesting today. But space travel has given astronomers new instruments to progress to greater distances and other spectral ranges. First the Hubble space telescope which ushered in a new age of astronomy in 1990 moved the location from which classical optical observations are made into space outside the Earth’s atmosphere. In the optical spectral range the earth-bound telescopes have in the meantime caught up with Hubble thanks to modern technologies such as adaptive optics and interferometry. The study of radiation which (lucky for us) does not penetrate the atmosphere or is highly interfered with in the process still remains the domain of satellites and space probes. In the shortwave range this is the gamma and X radiation and on the other side of the spectrum the infrared, submillimetre and radio radiation: it is in these ranges that Herschel and Planck work.
Space technology has also developed since 1990. In 1993 Iso, the first European satellite for infrared astronomy, was launched into an excentric 24-hour orbit around the Earth whose furthest point from the Earth was 60,000 kilometres away. Today, because of the availability of communications systems that have been developed for interplanetary missions, we would no doubt send Iso 1.5 million kilometres from the Earth to L2 as we are doing with its successor Herschel.

The Lagrange libration points
The position of the five libration or Lagrange points is shown in Fig. 1 and 2. These points were first described in theory by the mathematician Joseph-Louis de Lagrange (1736 -1813, Fig. 3) in the context of the 'restricted circular three-body problem', i.e. under the assumption that a body with mass $M_2$ (a planet) moves in a circular path around another larger body with mass $M_1$ (the Sun) and that the mass of the third body (for instance an artificial satellite) is very small compared to that of the first two. The gravitational forces of the two primary masses, in our case the Sun and the Earth-Moon system, then interact at the five libration points such that they ‘hold’ the third body (the satellite) there and it uniformly orbits the Sun in the same time (1 year) as the Earth.

However if we want to examine the problem in detail the Earth’s orbit must be assumed to be an ellipse, not a circle (the Sun is lies on one of the focal points, the Earth’s distance from the Sun varies over the course of the year between 147.1 and 152.1 million kilometres), and furthermore we must deal also with the Earth and the Moon separately and not simply regard their combined centre of mass as a second body. The libration points themselves are then no longer so easily described, and we rather become concerned with motions or ‘orbits’ around the libration points.

The two points $L_4$ and $L_5$ lie on the Earth’s orbit around the Sun 60 degrees ahead of the Earth and 60 degrees behind the Earth. These two points are dynamically stable which means that everything that gathers in its vicinity stays there. In the Sun-Earth system (and also in the Earth-Moon system) these points are rather unimportant from an astronautical point of view (as far as we know today); in the Sun-Jupiter system (distributed around the vicinity of $L_4$ and $L_5$) the asteroid family of the Trojans has gathered there.

The collinear libration point $L_1$, $L_2$ and $L_3$ are interesting for space travel as they all lie on the lines that connect the two larger rotating masses. $L_3$, which is positioned on the other side of the Sun, can hardly be reached. The points, which are becoming increasingly important for space travel not only in the Sun-Earth system but also in the Earth-Moon system, are $L_1$ and $L_2$. Satellites that are parked at $L_2$ in the Earth-Moon system ‘stand still’ above the reverse side of the Moon. Already in the seventies it was proposed that they be used as communications relays for a telescope on the far side of the Moon. In practice, such a relay satellite should not stay at the libration point itself but move around at some distance such that the Moon does not get in the line of vision to the ground station on Earth. Very new projects (‘Back to the Moon!’) intend to use L1, situated between the Earth and the Moon, as a ‘stop-over and repacking station’ for manned Moon missions.

In the Sun-Earth system the libration point $L_1$ lies 1.5 million kilometres (1/100 astronomical unit) away from the Earth in the direction of the Sun. As early as 1995 the Sun observatory SOHO (Solar Heliospheric Observatory) was placed on an orbit around $L_1$ by ESA and NASA.

The libration point, which in the last approximately ten years has become a favourite of space-supported astronomy, is $L_2$ in the Sun-Earth system.
**Instability and the stable manifold at L₂**

For all of us who ever had to sit through a mathematics lecture: The linearised differential equations of second order that approximately describe the motion in a rotating system (x-axis from the Sun to the Earth) have in addition to conjugate complex eigenvalues (which gives rise to periodic oscillations) also two real eigenvalues, one positive and one negative. The positive one is problematic generating an exponential term with positive exponent. The trick is to make the coefficient in front of this term (and also in front of the other exponential term) equal to zero by appropriately selecting the initial values. What remains is a periodic motion around the libration point. But even the smallest deviation from the path that corresponds to these initial values (those always happen for satellites) brings that term into play again and the satellite veers away exponentially (faster and faster) from the desired periodic orbit.

If we take the total non-linear dynamics into account, the second non-periodic term in the equations of motion as represented by the negative real eigenvalue generates a geometric structure in space called stable manifold from which satellites move into system. It lies on the line that connects the Sun and the Earth, 1.5 million kilometres outside the Earth’s orbit.

**Paths to L₂ and around L₂**

The collinear libration points, or more accurately the orbits around these points, possess an interesting dynamic duality. On the one hand they are unstable - a body will not stay there without active control. On the other hand, however, they have a quite contrasting property. From a certain structure in space (a type of curved surface), an object moves into an orbit around one of these points. This surface (Fig. 5) is called the stable manifold of the orbit around L₂.

Above we compared the unstable behaviour at L₂ with a mini-golf ball on a hilltop. A better comparison for this duality would be that of a mini-golf ball on a saddle, or even better a pass between two mountains: here we can also get an idea of the stable manifold, the ridge. This dynamic ‘ridge’ has proven to be extraordinarily useful to the Herschel mission. There are in fact orbits around L₂ whose stable manifold, i.e. the ridge, comes so close to the Earth that Herschel can be directly launched into this ‘vortex to L₂’ by the Ariane 5 rocket. The satellite then wanders freely along the ridge without any additional manoeuvring until it is on an orbit around L₂. In the process only small corrections are required to control the instability so that it does not fall down either side of the ridge.

Once in the vicinity of L₂ the motion of the satellite around the libration point can vary considerably. When certain initial conditions have been achieved in order to stay close to the libration point, the motion can be described well using the Lissajous figure shown in the box above. The Planck satellite will fly along a figure such as this.

If we move further away from the libration point the mathematical theory that describes the linear differential equations can no longer be applied as accurately. The periodic part of the motion still resembles an oscillation, however if the amplitudes of these oscillations around the libration point become even larger than those for the path shown above the non-linearities come into play even more strongly: The two frequencies of the oscillations in the ecliptic and at a right angle to it depend on the amplitudes of the oscillations. And we can in fact select the amplitudes such that the two frequencies become exactly the same. If we select the initial conditions well, a closed path (a proper orbit) around the libration point is created. This orbit, shown in Fig. 6, is called a halo. The Sun observation satellite Soho has since 1995 been moving along a halo such as this around L₁.
point like that of the light spot of a lamp placed in a swinging motion (Fig. 4).
In the case shown, one ‘revolution’ around the libration point takes around half a year (or more accurately: 177 days in the ecliptic and 184 days at a right angle to it). The cycle caused by the different frequencies up to the time the Lissajous figure is repeated takes around 13 years. The initial conditions of the path shown in Fig. 4 have been selected such that at the beginning the path just touches the Earth’s shadow (1.5 million kilometres behind the Earth the penumbra has a radius of 13,000 kilometres; the umbra ends at one million kilometres). It then takes more than six years (half a Lissajous cycle) before the path enters the umbra again. This property is important for space missions as the satellites depend on the Sun’s energy and therefore must fly around the Earth’s shadow.

The further we fly from the libration point the more inaccurately the linear differential equations describe the motion. The deformation of the rectangle that encloses the Lissajous figure in Fig. 4 results from taking non-linear effects into consideration when generating the orbit shown with an amplitude of 300,000 kilometres for the two separate oscillations.

Halo orbits extend far outside the penumbra of the Earth. Here sunlight is available continuously to generate energy. Orbits with large amplitudes are also easily reached - for example we are able to reach Herschel’s orbit on its stable manifold ‘freely’ without any manoeuvres.

For orbits with small amplitudes the stable manifold does not extend to close to the Earth. It can nonetheless be reached by ‘jumping’ from one manifold to another (at the points where they cross). This is done using an orbit manoeuvre, i.e. changing the speed by opening the satellite’s thrust jets for a short period of time to accelerate. A transfer with manoeuvres such as this will be necessary for Planck, as shown in Fig. 7. This increase in velocity is seen as a corner in the projection onto the ecliptic (the x-y plane), and then we see how the path leads into the Lissajous orbit exponentially. The duration of the Planck mission is only two and a half years and therefore we can only see a part of the entire Lissajous figure on the right-hand projection wall. We will return later to the question of why an orbit with a small amplitude is preferred for Planck.

Even if strictly speaking the libration point may not exist in the real world, we can conclude from the numerical calculations that there exist orbits around it and that these orbits have inherited the essential properties described by simplified (ancient) linear mathematics, in particular their instability and the existence of the stable manifold.

**The reason why a fleet of astronomic satellites will populate L₂**

The obvious advantage that libration point L₂ offers to space astronomy is that the Earth, and to a certain extent also the Moon, always lies in the same direction as the Sun as seen from the telescope location. The motion of the Earth around the Sun over the course of one year then allows observations to be made in every direction without having to point the telescope near the Sun or the Earth. Not so obvious but even more important is that this special geometry allows the satellite telescope to be designed to have a single shield that catches all thermal radiation. Under this condition and with the right insulation the CCDs in the focal plane can to a large extent be passively cooled – thereby reducing the thermal noise. However the low CCD temperatures necessary for the instruments on Herschel and Planck cannot be achieved purely passively.

For this reason the two satellites have additional cooling systems, one of them with a large container of liquid helium and the other with cooling pumps in accordance with the refrigerator principle.

On orbits that come closer to the Earth the radiation from the Sun can be shielded but the infrared radiation from the Earth falls onto the reverse side of the satellite with each revolution. In the case of Herschel, for example, more helium would have to be vapourised for cooling and during one part of the orbit no observations would be possible at all.

When carrying out a mission at L₂ the large distance is disadvantageous as it significantly handicaps communication compared to a mission closer to Earth. But this disadvantage has been eliminated due to technological advances.

The two technological developments that make a mission possible 1.5 million kilometres from the Earth are: firstly, the transition from the S-band (two gigahertz) to the X-band (eight gigahertz) for the transmission of data, and second, the availability of lighter and smaller data storage units. The tiny USB stick costing Euro 9.99 and second, the availability of lighter and smaller data storage units.

Fig. 5: The stable manifold of an orbit around L₂ has the shape of a pipe that goes backwards in time from the orbit around L₂ to the vicinity of the Earth. The distances on the axes are shown in kilometres from Earth.
Fig. 7: The path of the Planck satellite: Transfer and two-and-a-half year drift phase around the libration point. The transfer begins on the same path as for Herschel. The twin launch on the Ariane 5 almost delivers the two satellites onto the same path (a little different in order to avoid a collision). Planck will then jump onto the stable manifold of the path with the smaller amplitudes.

Further into the future we have XRO and Darwin (circa 2020):

- XRO is an X-ray observatory. It comprises two satellites: The 'mirror' and focal plane will fly separately but their relative positions must be controlled with extreme accuracy.
- The most demanding of the missions that are currently in planning for $L_2$ is Darwin. The mission comprises three three-metre mirrors that fly separately, as well as a relay satellite. In its search for life Darwin is expected to resolve the waterline in the spectra of terrestrial planets near other stars. Details can be found on the websites of the ESA projects.

The launch window towards the halo and Lissajous orbits around $L_2$ For Herschel an orbit around $L_2$ has been selected which can be reached along the stable manifold without requiring the satellite to make its own manoeuvres.

The launch pad of the Ariane 5 in Kourou is firmly on the ground. Three seconds prior to lift-off an 'inertial guidance platform' is initialised on the rocket, whose accelerometers and gyroscopes together with complex software ensure that the satellite is delivered as accurately as possible to the pre-defined target conditions.

Today's large (hardened) data storage units allow observations and data transmission to take place at different times. The data is stored while the observations are made and then the satellite is pointed in the direction of the Earth for four hours daily for the purpose of data transmission - always at a time when the ground station on Earth is on the night side (it is then visible from $L_2$). A mechanically movable antenna could also be mounted on the satellite, but antennae of this sort are more susceptible to failures and therefore less popular.

The data rate from a satellite antenna to a ground antenna using a certain transmitter power is inversely proportional to the square of the distance and it is also proportional to the frequency. Therefore the data rate in X-band is the same as for S-band at four times the distance. The transition to the X-band technology was accelerated at ESA prior to 2003 in particular due to the interplanetary missions Mars Express and Rosetta. For these projects ESA also has built two ground stations with 35-metre diameter antenna dishes, one in West Australia and one near Madrid. The ground antennae of the previous generation had diameters of only 16 metres. Our two astronomy satellites will benefit from the new large antennae in connection with the X-band technology.

The concerns of those responsible regarding the instability of the trajectories at $L_2$ were dispelled as a result of the experiences with Soho (more than by the mathematical analyses). Since 1993 SOHO has been demonstrating that an orbit around a collinear libration point can be maintained against the instability. Although SOHO once lost its attitude control, which led to the thrust jets freezing and it leaving the halo path, it was able to be rescued and is still in operation today. A small to be mentioned advantage of this instability is that unlike geostationary satellites we do not have to worry about what will happen to the satellite at the end of its active life to ensure it does not disturb the other satellites: The area surrounding $L_2$ is self-cleaning.

For Herschel and Planck paths at $L_2$ were clearly preferred over other options due to the favourable associated geometry. The same decision was made by NASA with respect to the James Webb Space Telescope (the successor to the Hubble space telescope) and by all of the space agencies for a range of other astronomy missions. At ESA this includes the following:

- Gaia, an astrometry mission whose launch is planned for 2011 or 2012 and which is expected to achieve an astrometric accuracy that is one thousand times higher than its successor Hipparcos. Particularly important for Gaia is the thermal stability of the optical bench on which the two telescopes that simultaneously peer into two different directions are mounted and thus measure the sky. The stable conditions at $L_2$ are especially favourable for this.
The Earth rotates and the orientation of the launch pad relative to the direction to L₂ (away from the Sun, midnight) must lie in a certain range in order to enter the stable manifold of an orbit around L₂. This defines the possible times of the launch. This interval of time for each launch date is called the launch window.

Until now we have considered the stable manifold as being backwards in time from the path around L₂. Conversely, it can be shown that for a launch at a certain time with fixed delivery conditions for Ariane in a system that rotates with the launch pad, one specific orbit around L₂ will be attained. Only a small correction in velocity two days after the launch is necessary. The trajectory at which Herschel arrives at L₂ is different for each launch date and each launch time and is by no means always a proper halo orbit.

For the double launch together with Planck, the joint launch window must also fulfill the conditions of the Planck mission. Herschel is an observatory that observes individual astronomical objects. Planck is a scanning mission, which means: Planck will systematically cover the entire sky in order to map the microwave background radiation.

While Herschel will point towards the Earth each day for four hours in order to transmit its measured data, Planck must not interrupt its systematic circling across the sky. It must continually rotate at one revolution per minute and points its axis, around which it turns, towards the Sun (and therefore also towards the Earth!), such that the satellite itself always remains shielded from sunlight by its solar cells. The transmission of the data to the Earth can therefore take place continuously using an antenna that is fitted exactly to the axis of the satellite. In order to be able to transmit the necessary amount of data an antenna with directivity is required, or more accurately a horn antenna with a half cone angle of 15 degrees. This means that as seen from the satellite the Earth cannot lie more than 15 degrees from the Sun. This translates into a condition for the two Lissajous amplitudes of the target path of approximately $A_y = A_x = 280,000$ kilometres.

Halo orbits and all orbits around L₂ that can be freely reached typically have $y$ amplitudes of more than 800,000 kilometres. This means that Planck must be put onto a Lissajous orbit, and this cannot be done without a major orbit manoeuvre. This manoeuvre uses more or less fuel depending on the launch date and launch time. The tank size of the Planck satellite has been selected such that it provides a large enough launch window.

The launch windows that are possible over the course of a year taking these conditions into account are shown in Fig. 8. It soon becomes clear that Planck would consume too much fuel in summer - the launch window at this time is completely closed. The times that must be excluded because the satellite would otherwise fly into the umbra are around the time of the equinoxes. Two important conditions (Sun aspect angle) which will not be discussed here to have to do with the fact that during the launch the Sun must not shine from above onto the satellites that are mounted on top of the rocket (Fig. 9). The green ranges form the final launch window which takes into account additional restrictions for Herschel.

As we can see from Fig. 8, the joint launch of Herschel and Planck takes place in the early afternoon (Greenwich time), i.e. in Kourou at 52 degrees west in the morning.

**Operations of the Herschel and Planck satellites**

Fig. 9 shows the two satellites ready to be launched on Ariane 5. The outer casing of the rocket will be shed 190 seconds after the launch when heating due to a change in the launch support from the ground is required for this. Simply put, we measure the time it takes for the signals to travel from the satellite ‘knows’ its status thanks to various measuring sensors on board. It can also determine the orientation of its axes (its attitude) itself relative to an inertial system. A small wide-angle telescope is used here: The software on board compares the observed star pattern with a catalogue until it knows what the telescope is currently viewing. From this it is able to derive in which direction that telescope is looking and also how it is turned on its axis, and as a result knows the alignment of the satellite.

However, the satellite is unable to measure its own position and velocity: support from the ground is required for this. Simply put, we measure the time it takes for the signals to travel from the

![Fig. 8: Launch window for the joint launch of Herschel and Planck on an Ariane 5 in Kourou. All of the conditions that cannot be infringed upon are marked in different colours. The launch is able to take place in the remaining green area. Note that the launch window has changed due to a change in the launch orbit. It is now open through summer.](image)
ground station to the satellite and back, divide it by twice the speed of light and from this we calculate the distance. The satellite moves in accordance with known laws of physics, the ground station rotates with the Earth - the statistical problem of defining the six position and velocity coordinates that describe a satellite orbit such that the path matches the distance measurements remains to be solved - for example by minimising the sum of some squares of errors. Apart from the distance measurements, the frequency shift, mainly generated as a result of the motion of the ground station, is used to derive information about the position of the satellite at right angles to the viewing direction.

In the control centre (Fig. 11), therefore, the satellite is monitored and remotely controlled, its trajectory is determined, deviations from the desired target trajectory are calculated, and then commands are sent to the satellite to open certain jets which are able to turn the satellite to then generate a kickback in a desired direction. The force generated, divided by the mass of the satellite, corresponds to an acceleration - integrated over a time interval this results in a change in velocity. In space there are no roads and nothing that can be used to hold onto or push off from: Only the velocity can be changed - for example by blowing off fuel. A relatively small change in the velocity of the large satellite mass is achieved by a flow of fuel gasses that exit the thrust jets at high speed (conservation of momentum!).

Unlike a car or a machine on Earth we cannot simply go to a satellite, screw it open and repair it. If there are problems we must determine from afar what is not working and why. Specialists in various areas are required for this, as are very detailed procedures comparable to the checklists that airplane pilots have. As there is no possibility to carry out maintenance on satellites, the important systems are installed twice and, most importantly, satellites are very rigorously tested prior to launch. As a result breakdowns occur relatively seldom in space.

Before our two satellites Herschel and Planck can begin to align their telescopes and carry out the scientific measurements, all of their functions must be carefully checked and adjusted. This is done by remote control, analysing the telemetry and the data from the satellite and by sending tele-commands to the satellite.

Immediately after Planck has performed the delivery manoeuvre onto the Lissajous orbit (or more correctly, onto its stable manifold) the science begins. From this point onwards, large amounts of scientific observation data are transmitted from the satellite to the ground station daily and from there via terrestrial lines to the control centre in Darmstadt, and from there onward to the scientific institutes. In the routine phase of the missions only the ground station in Australia will be used. As a consequence, only day shifts are required at the control centre in Darmstadt.

All of the parameters that describe the status of the satellite are always sent together with the scientific data and if necessary there is immediate intervention in the form of a command from the ground station: computer programs are changed on board or control parameters are simply re-set. At the same time the orbit is continually monitored and every four weeks a trajectory correction is carried out as the orbits at L₂ are, as we know, unstable and nothing will remain there without active control.

**Mission Analysis**

A scientific project at the European Space Agency (ESA) is first created as the result of proposals from European scientists and their institutes. From this wealth of ideas a few are selected that can be realised within the framework of ESA’s scientific budget. Projects are evaluated by various committees according to their scientific content relative to the costs. Feasibility studies always form a part of this selection process, which means that studies are made as to how a proposed project can be carried out and what it would cost. This involves making a preliminary design of the satellite. This cannot succeed without knowing on which orbit it will fly in order to best fulfill its scientific purpose - this means that it cannot be done without a mission analysis.

The heart of the mission analysis is selecting the orbit and the associated optimisation of manoeuvres and fuel estimation. In addition, a multitude of geometric parameters must be calculated for the design of the satellite - for Herschel and Planck, for example, the time evolution of the viewing angle to the Earth relative to the direction of the Sun and the visibility of the satellite from the ground station and the times that the penumbra of the Moon is moving over the satellite at L₂.

Obviously the design of suitable trajectories is a key element of planning interplanetary missions. Such projects usually require new ideas and new methods, and seldom require routine work. In this manner the mission analysts at ESOC support all of ESA’s interplanetary projects, the projects that are finally carried out represent only a small fraction of the proposals investigated.

The interplanetary program of ESA that has actually been carried out...
out began with the Giotto probe that flew past Halley’s comet in 1986. After this came Huygens, the probe that was launched in 1997 and carried to SATURN by the NASA satellite Cassini and which landed on Titan, one of Saturn’s moons, in January 2005. This was followed by Mars Express which swung in a path around Mars at Christmas 2003, and its ‘clone’ Venus Express, which has been in use near Venus since the beginning of 2006. We must not forget Rosetta, which since 2004 has been on the way to closely investigating the comet Tschurjumow-Gerasimenko - a complicated ten-year tour that is using close fly-bys of the Earth and Mercury in addition to the gravitational assistance from Venus and Mercury itself, BepiColombo will need a new ion engine (see SuW 7/2007, p.26ff).

The trajectory calculations must be correct 'down to the last kilo'. At this point in time the mission analysis must be done by the launcher. Among other things, one satellite contains more than one hundred kilograms of data and power lines, enough to wire a whole house. As a result the mass of the satellite generally continually increases over the course of its development. If the mass of the satellite grows, the fuel mass must be reduced as the two must be launched together by the launcher. Another aspect of the mission analysis must be to select a suitable launch rocket, an estimation of the launch mass to an accuracy of ±0.1% is required momentum for a rendezvous with the comet in 2015. Even more complicated than Rosetta is the BepiColombo mission that is currently prepared for a journey to the planet Mercury. In order to reach it relatively quickly (it will still take six years), in addition to the gravitational assistance from Venus and Mercury itself, BepiColombo will need a new ion engine (see SuW 7/2007, p.26ff).

The trajectory calculations must become increasingly accurate over the course of developing a project. At the beginning, when selecting the most suitable launch rocket, an estimation of the orbit can be predicted. It is not only fuel that has to be loaded in order to carry out the nominal changes in velocity that are required to reach the target orbit; we also need to be prepared for inaccuracies and contingencies. The first large inaccuracy is the deviation of the trajectory onto which the launch rocket delivers the satellite from that which was actually planned. Correcting this initial error can use a lot more fuel than holding the unstable orbit around L₂.

Interesting web links on this topic can be found under www.esa.int/science.