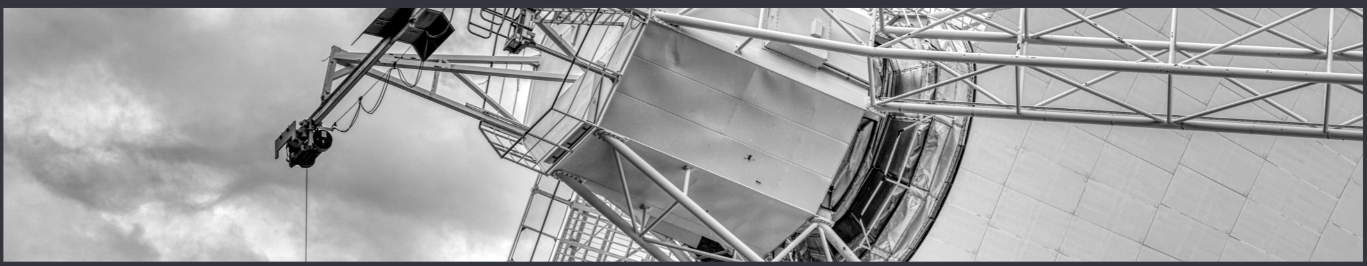
ONCE YOU START ASKING



PREVIEW

SOFIA

Telescope Architecture and Control

INSIGHTS, STORIES AND EXPERIENCES

from ten years of reporting on science and engineering

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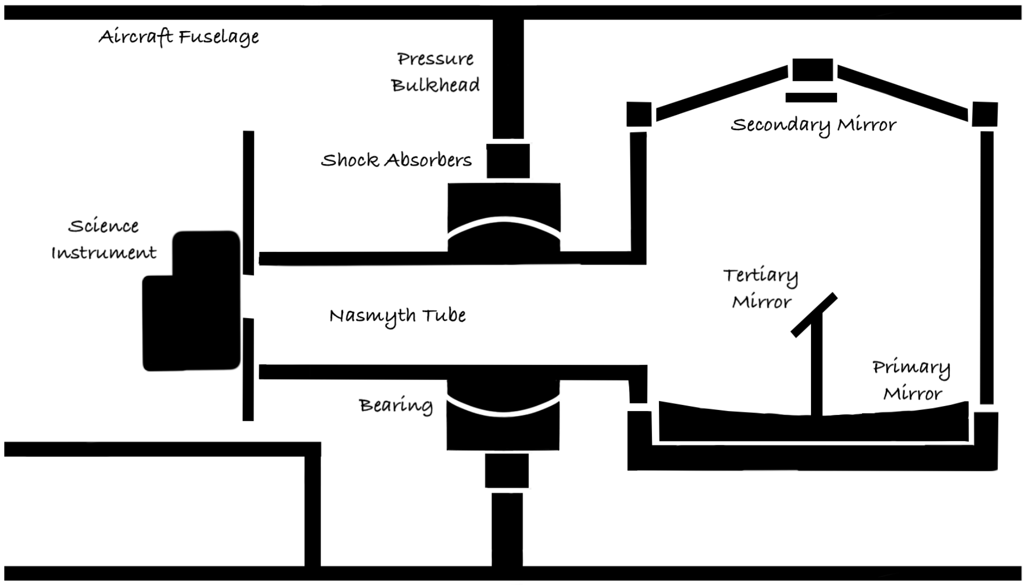
A Nasmyth telescope. SOFIA uses a Nasmyth telescope, which is fundamentally arranged in a dumbbell shape. Its relatively compact vertical size makes it ideal for fitting into an airplane. It consists of three major parts: a set of mirrors for collecting and guiding the infrared radiation, a (replaceable) instrument that analyses that radiation, plus a massive carbon fibre construction that connects these two and serves as the structural backbone for the whole telescope, the so-called "Nasmyth tube". The complete telescope weighs 17 tons; the movable parts held by the Nasmyth tube weigh 10 tons.

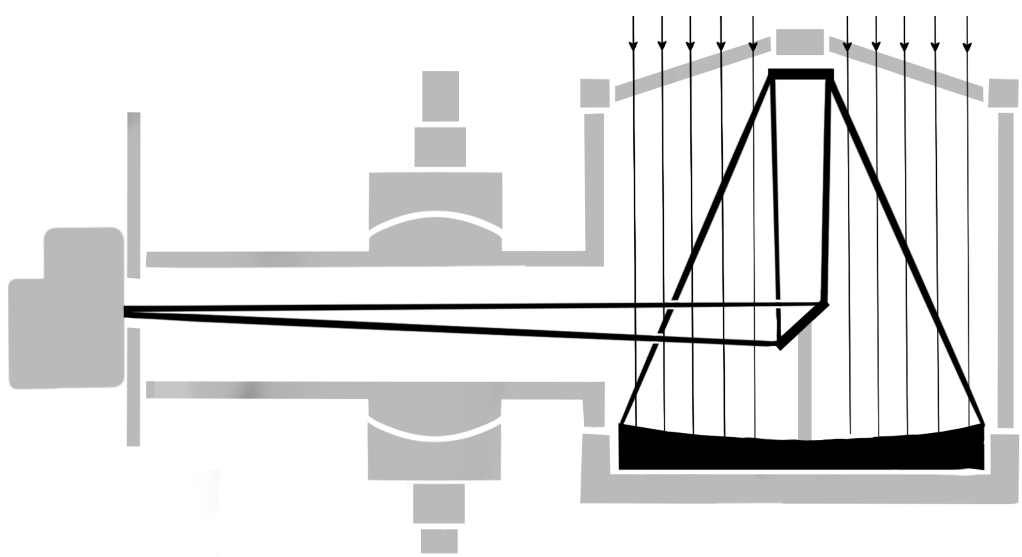
An airplane's cabin is pressurized to roughly 10,000 ft when it is at its operational altitude of 30,000 to 40,000 ft. However, the tail section of a commercial airliner is not. The pressure vessel that constitutes the cabin ends with the aft bulkhead, a strong circular structure that can withstand the pressure difference between the cabin and the unpressurised rear part of the fuselage. The same is true for SOFIA, but this bulkhead is moved forward significantly. This is because the telescope has to be in the unpressurised section, the so-called telescope cavity, since the open door exposes this part of the observatory to the external low atmospheric pressure. On the other hand, it was decided to put the instrumentation into the pressurized part of the cabin to simplify in-flight monitoring and diagnostics. So the light that is collected in the unpressurised part somehow has to make its way into the pressurized section for analysis in the instrument. The Nasmyth tube plays an important role here: it is sturdy enough to act as the backbone onto which the telescope and the instrument are mounted, but it also is hollow, so the light can pass through from the mirror assembly to the instrument mounted at the other end. This illustration, adapted from a similar one by DSI, provides an overview.



The Nasmyth tube itself is carried by a bearing that installed in the bulkhead that allows the telescope to rotate in elevation between 17 and 65 degrees from the horizon. This corresponds to a rotation around the long axis of the Nasmyth tube and is achieved by a motor-driven cog/wheel assembly. To point the telescope at a particular target, in addition to elevation you also have to control azimuth, the "compass direction" at which the telescope is pointing. The telescope itself has (almost) no means of changing the azimuth; instead the airplane has to change its heading to control the direction of view. The desired observation targets for a particular mission therefore govern SOFIA's flight path for that mission—an interesting challenge for flight planning, as we will see later.

What I wrote above is not quite true: in fact, the telescope can rotate by ±2.5 degrees in azimuth. This is achieved by means of a spherical bearing inside the cog/wheel, which is in turn mounted inside the aft bulkhead. The bearing also provides ±2.5 degrees of control in elevation, as well in a third axis in order to track the sky's rotation and keep the image's orientation stable. These ±2.5 degrees in all three directions are the domain of the fine drive, managed by the telescope control system, which I will explain in the next section.

The telescope itself has three mirrors. The main mirror, at the bottom/rear of the telescope, is 2.7 meters in diameter. This reflects light to the secondary mirror located the top/front of the mirror assembly. The fact that this mirror is in front of the main mirror means that SOFIA, like all reflector telescopes, has a small blind spot in the middle of its field of view. The secondary mirror reflects the light onto two tertiary mirrors positioned about two-thirds of the way along the telescope's axis. These are both arranged at a 45-degree angle and reflect the light through 90 degrees into the Nasmyth tube. The upper of the two tertiary mirrors reflects infrared light into the instrument but it is transparent to visible light; this strikes the lower tertiary mirror and is reflected into the focal plane imager, an optical camera that is used mainly for tracking. Occasionally the focal plane imager is also used for science, making SOFIA also an optical telescope that can be moved around the planet to observe interesting phenomena such as occultations, where the airplane has to be at a very specific point in time and place to make meaningful observations. It's not the world's greatest optical telescope, but it's unique in its ability to move to places of interest.



Two more things are worth mentioning here. First, in addition to the cog/wheel drive and the spherical bearing, the mounting of the telescope in the bulkhead also features passive mechanical dampers to filter out high-frequency vibrations—the vibration isolation system. These are composed of air springs, essentially like rubber tires: there are no metal-to-metal contacts between the telescope and the airframe when the telescope is operating. During take-off and landing, though, the telescope is secured by pressing it against metal hard stops.

The second interesting tidbit is that, as the outside atmospheric pressure extends through the Nasmyth tube to the instrument, the instrument's entry window must be able to bear that pressure differential. It does, although since this window has a very small surface area, the resulting force is relatively small.

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Actuators. As with any control system, it's all about sensors and actuators. Let's start with the actuators. I mentioned the 1.2 meter spherical bearing and the fine drive before. Let's look at it in detail. As indicated before, it can move the telescope in three directions to follow the sky's rotation and keep an image's orientation stable: elevation, cross-elevation and line-of-sight. This movement is achieved with electromagnetic torquers: the inner, movable sphere of the bearing contains the magnets, and the outer, static cradle contains the coils. This kind of electromagnetic actuation is very precise, but cannot create huge forces. This means that the friction of the bearing must be reduced as much as possible. To achieve this, oil is pressed into the 15-micron gap between the sphere and the cradle. The whole ten-ton movable part of the telescope therefore rests on an oil film! This arrangement is so delicate that the temperature of the sphere and cradle have to be controlled precisely. For example, if the inner sphere gets too cold, it shrinks, reducing the 15-micron gap and risking the metal of the sphere touching the metal of the cradle. This would destroy the fine drive's ability to control the telescope precisely. The temperature of the whole bearing is primarily controlled by the temperature of the oil used for lubrication. The SOFIA's cold cabin also helps, although it is sometimes annoying for the crew and leads to the kind of interesting headwear shown below.

For the forces of the fine-drive torquers to be sufficient, it is also crucial that the two main masses—the telescope on one side and the instrument on the other—are perfectly balanced. The telescope is usually heavier than the instrument, so additional weights are installed on the instrument side around the instrument mounting flange. Whenever an instrument is installed (for example after an exchange) the system has to be rebalanced. This process starts by attaching a set of counterweights whose weight is based on previous experience. The fine drive is then activated and the team measures how much force it has to create in each direction to keep the telescope balanced. The weights are then adjusted until these forces are zero. There's a complication, though: most instruments become lighter during a flight because they consume coolant. Some of the counterweights are therefore installed on a drive that can move outward with time, increasing their leverage. The balancer drives move the weights at 0.0012 to 0.0036 millimeters per second, using an open control loop based on empirically derived values for the instrument's rate of consumption of coolant. All these steps ensure that the ten tons of the telescope can be moved by magnetic torquers. In fact, Oliver remembers that "the whole telescope can be moved with your pinky once it's balanced."

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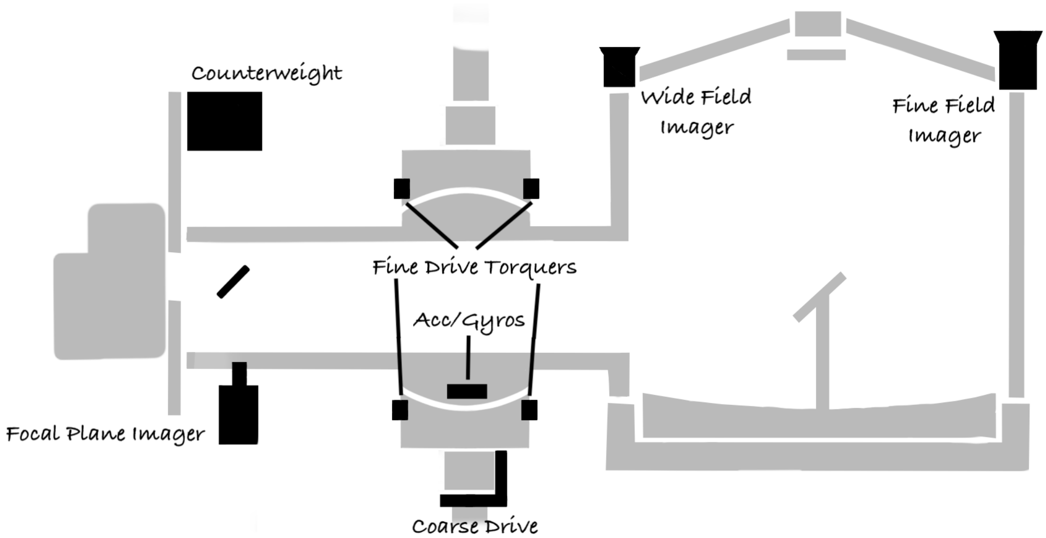
Sensors. Let's move on to the sensors. The telescope is "attached" to a guide star by optical cameras of which the telescope has several. The one used primarily for tracking is the focal-plane imager, which looks through the Nasmyth tube and the telescope. It has a relatively narrow field of view, around 8.5 arc minutes (although this is still wider than the field of view of the instruments, which range from 8 arc minutes to 6 arc seconds). It is possible that for a particular observation, no optically visible guide star is "in the picture". In this case SOFIA can also track using the fine-field imager, a camera with a slightly wider field of view mounted on the telescope ring; it does not "look" through the telescope. The third optical camera, the wide-field imager, also mounted on the telescope ring, is mainly used for initial targeting, where an even wider field of view is useful to position the telescope relative to the wider neighborhood of the target.



To keep the telescope locked onto a particular target, a controller tries to keep the guide star image seen by the tracking camera at the same location. There is a problem, though. Depending on the brightness of the guide stars, the cameras have an integration time of half a second or even a second. This would would make the control loop very slow and thus imprecise. This is why the telescope also has several fiber-optic gyros that detect acceleration and attitude in all relevant dimensions. Their signals can be used to interpolate between the subsequent guide camera updates.

You might ask why the gyros aren't used exclusively. Gyros drift over time, so a gyro might report a very small acceleration when in fact the situation is stable. The guide cameras provide an absolute signal and can thus be used to reset any gyro drift computationally; the cameras and the gyros work together to keep the telescope's attitude stable. In addition, from a control theory perspective it is useful to acquire not only the set value and the actual value as inputs to a control loop, but also the derivative of the actual value; some control algorithms take the derivative into account explicitly to improve precision. The gyros report that derivative much more precisely than the pixel movement of an image derived from the guide cameras.

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Control Requirements. To achieve good image quality the telescope must be precisely locked onto its observation target during exposure. The longer the exposure, the more important a stable tracking becomes to avoid "blurry" images. A telescope that is mounted on a moving platform must itself move actively to compensate for movement of that platform. Every earthbound telescope does this to compensate for the rotation of the Earth, which is roughly 1.600 km/h at the equator. SOFIA's telescope is built on an aircraft that moves at around 800 km/h. Both are in the same ballpark, and similar means of compensation can be employed. So, like professional ground-based telescopes, SOFIA uses a closed control loop that fundamentally relies on tracking guide stars.

However, the SOFIA telescope controller also has to compensate for turbulence, smaller but unpredictable disturbances of the otherwise predictable flight path of the host aircraft. Flying in the stratosphere, SOFIA is above most of the weather, and thus above most of the turbulence, but turbulence nevertheless does occur. This makes the controller much more sophisticated than the one for a ground based-telescope. SOFIA's telescope engineer, Oliver Zeile, explained it to us. Together with his DSI and USRA team, he is responsible for readying the telescope for a flight and operating the telescope during the flight.

Before we can continue, we have to talk about coordinate systems. In the sky's absolute coordinate system every point can be identified by elevation (the angle above the horizon) and azimuth (the compass direction). Many telescopes mounted on earth use exactly these two axes for pointing. Using a control loop, these two axes are also sufficient to follow the (apparent) rotation of the night's sky.

As we have seen in the previous section, however, SOFIA's telescope is mounted on a bearing in the bulkhead which allows rotation around three axes for pointing and tracking. These three axes form their own, telescope-local coordinate system. One axis, elevation, is similar in both coordinate systems: the telescope can rotate up and down. The other two axes are different, however. They are called cross-elevation and line-of-sight. To understand how they are aligned relative to azimuth, let's run a thought experiment. I suggest you follow along with your hands to visualize the situation.

Let's assume we could point the telescope completely horizontally and straight up, changing the elevation between 0 and 90 degrees. Now let's say the airplane changes its heading and thus changes azimuth (in the sky's absolute coordinate system). If we have the telescope pointed at zero elevation, then a change in azimuth maps completely to a change in cross-elevation. If instead the telescope were pointed straight up, a change in azimuth would map to a change only in line-of-sight. For all practical elevations between 17 and 65 degrees, a change in azimuth always maps to a change in both cross-elevation and line-of-sight, using a coordinate transformation that involves the sine and cosine of the elevation angle. The point is: the telescope's control loop, which we will discuss next, works in the elevation/cross-elevation/line-of-sight coordinate system, while the scientists care about elevation and azimuth, and how this changes as the sky rotates.

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Control Strategy. Let's recap: the coarse drive is used to put the telescope into an elevation that is suitable for the observation target. The heading of the airplane provides the correct azimuth. As the airplane and the sky move, the fine drive compensates for both by moving the telescope assembly in the telescope's elevation/cross-elevation/line-of-sight coordinate system relying on the coordinate transformation mentioned earlier. But remember, it only has 2.5 degrees of travel in each direction. So what happens when the fine drive reaches its limits? What actually happens differs for each axis. For elevation it is simple. Say that the fine drive runs into its upper limit. The coarse drive can then simply move up while the fine drive compensates for this movement by moving down by the same amount, effectively resetting its own range of travel. This is done automatically by the telescope controller, continuously, in small steps.

For the other two axes it is more complicated. As we have seen before, they "share" the aircraft's movement in azimuth depending on the elevation. Said differently: if we run into the 2.5 degree limit of the fine drive, the cross-elevation component can be compensated by a change in azimuth: the mission director tells the flight crew to turn the airplane left or right by a degree or two. Integration of the telescope controller with the 747SP's autopilot has been discussed for a long time. This would allow heading changes to be automated, avoiding the need for the mission director to tell the pilots when to change heading. However at the time of my flights this was not available, and the pilots said that they were happy to carry out manual corrections, as during cruise they didn't have very much else to do anyway.

The other component, the rotation around line-of-sight, cannot be compensated transparently by a movement of a drive or the aircraft. Instead, the telescope has to be explicitly "rewound". This means that the orientation of the "picture" seen by the telescope actually changes (which is relevant if the target is not point-symmetric). So, while the reset in elevation and cross-elevation are transparent to the telescope and do not impede the instrument's data collection, this is not true for the line-of-sight rewind, whose timing is therefore coordinated with the instrument. A rewind takes roughly a second, and, depending on the observation's target and the position of the airplane, a line-of-sight rewind is necessary every three to 20 minutes.

What is intriguing about the attitude control of the SOFIA telescope is that it requires no explicit coordination with the aircraft's movements in the sense that it needs to be integrated with the aircraft's systems—or with the coarse drive, for that matter. If the aircraft turns, or if the coarse drive rewinds in elevation, the fine drive continues with its usual job of keeping the target locked, just as for any other disturbance such as turbulence. The telescope is stabilized inertially. In fact, controlling SOFIA's telescope closely resembles the control of a satellite, which is why the team includes satellite people. Oliver's PhD, for example, was in satellite attitude control. There are many videos on YouTube showing the telescope moving inside SOFIA's fuselage. These videos are sped up to make it easier to see the effect, but I was able to see the movement by carefully observing the instrument in the fuselage. Of course it is the fuselage that moves around the telescope: the telescope is stable in space, locked on to its target. Quite impressive, if you think about it.

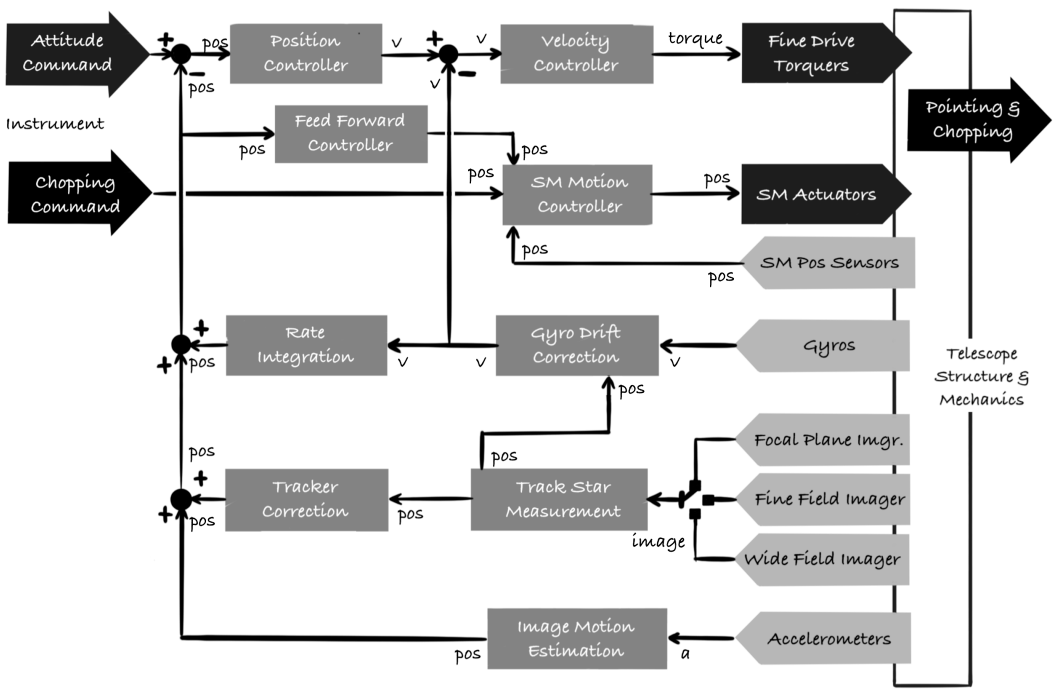
There is one more complication. The whole reason for mounting an infrared telescope on an airplane is that this allows it to be high enough to avoid problems caused by water vapor in the atmosphere. However, even at SOFIA's altitude, 99% of the radiation collected by the telescope (and thus, the instrument) comes from the atmosphere (and the telescope itself). This atmospheric noise fluctuates on a scale of seconds to minutes. To get the signal-to-noise ratio to a reasonable level and produce a meaningful observation, SOFIA also collects data from the background "dark atmosphere" and subtracts this from the data that includes the signal from the target object. The instrument is aware of the difference in these data sets and processes them correctly. To collect the atmosphere-only data, the attitude of the telescope is periodically shifted to a location in the sky close to the target to capture a signal from the same part of the sky but without the target object. This happens at a frequency of 2 Hz and is achieved by moving the secondary mirror in a process referred to as "chopping". Moving the heavy primary mirror at this high rate would be infeasible. The requirements for chopping limits SOFIA—or any other infrared telescope, as chopping is standard practice—to observing targets that have "empty" space close to them.

Chopping leads to another problem, however. The primary mirror is relatively massive, so one cannot assume that it is at exactly the same temperature over the whole of its surface. Because the secondary mirror, during chopping, "looks" at different parts of the primary mirror, it might see different temperatures at various parts of the primary mirror. Those temperatures affect the signal. "It's almost as if a different telescope were used for the actual target and the chopping target", says Christian Fischer, an instrument engineer. To compensate for this effect, the primary mirror moves as well, in a process known as "nodding". This essentially flips the locations of the actual target and the chop area on the main mirror, canceling out the "two different telescopes" effect. The nodding process happens on a longer timescale and is achieved by the fine drive moving the whole telescope.

This chop/nod scheme explains why two different numbers for the size of SOFIA's primary mirror exist. Physically it is 2.7 meters in diameter, but effectively only 2.5 meters can be used; the rest of the mirror's surface is not "seen" at any setting of the secondary mirror. The "extra" 20 centimeters are necessary for nodding.

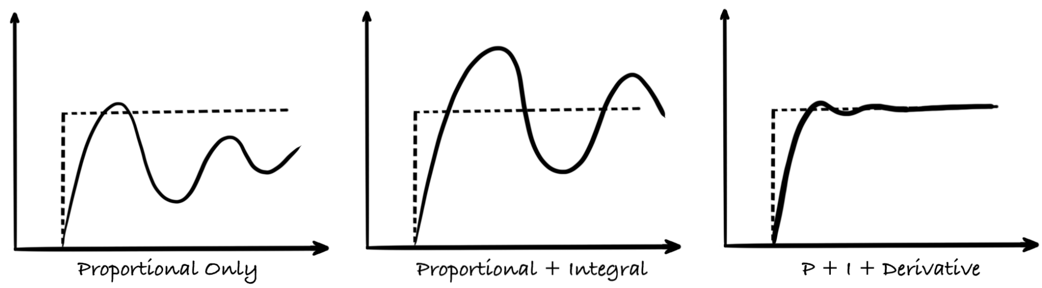
During an observation the telescope is controlled by the instrument attached to it: the instrument is in charge of "running the show". The reason for this is that the instrument's data acquisition must be coordinated with whatever the telescope does (chopping, rewinding) for it to be meaningful. Around 50 parameters have to be set for every specific observation, including the position in the sky and the configuration of the chop/nod scheme. Hundreds of such parameter sets have to be generated for each flight. This is done with scripts written in the programming language IDL—similar to Python—which is also used for data reduction.

Here is the overall high-level control algorithm, courtesy of Oliver Zeile. Of course there is lots of math going on in many of these boxes.



Note how the gyros directly feed data into the velocity controller (and do not just go through the position controller). This allows the algorithm to take into account the first derivative of the quantity the system is controlling, the position, allowing for faster reaction to disturbances. Fundamentally, this is a PID-controller: a control algorithm that takes into account three components. The first one is the proportional component. It creates a response that is proportional to the error between the set value and the measured value.

Because it needs an error to generate a response, a pure P controller will never quite catch the actual value up with a new set value. The diagrams below show a signal (dashed line) that changes at some point in time. The actual value oscillates, but when it eventually stabilises, an error will remain.



This is where the integral part comes in. It integrates (sums up) the historic error and adds this to the response. So, while an error still exists, it increases its response, which is why it eventually pushes the error to zero. At this point, nothing more is added to the error and the system stabilises at the new set value. However, as you can see from the second diagram above, it still oscillates a lot around the set value. The derivative part "anticipates" this by considering the first derivate of the actual signal. Once all factors are tuned correctly, this dampens the oscillation significantly. But for this to work, it requires access to the derivative. It could be calculated from the changing set value, but measuring it directly, as the gyros do, help.

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