Hi this is Steve Nerlich from Cheap Astronomy www.cheapastro.com and this is *Spacecraft navigation.*

Navigating a robotic spacecraft remotely from Earth across distances measured in millions or billions of kilometres is a tricky business. Indeed, here you can say that it actually is rocket science. NASA's Jet Propulsion Laboratory (JPL) has published an excellent resource called *The Basics of Space Flight*, which you can easily find with a search engine, because who the heck types in URLs these days.

Nonetheless, if you prefer to listen to a layperson spending eight and a bit minutes struggling to make sense of spacecraft navigation – well, here goes.

Before you can start thinking about navigating a distant spacecraft, you first need to know where exactly it is. Now, flying around the solar system is a reasonably predictable business since if you are not firing your rocket engines, your trajectory is essentially a solar orbit, which is influenced by your initial momentum but otherwise entirely determined by gravitational forces exerted by the Sun or other massive bodies nearby.

So if you knew where your spacecraft was yesterday, a bit of Newtonian or Kepler-esque number crunching can you tell you where it is today – well, more or less. But you know, more or less isn't really going to cut it in the spacecraft navigation business.

This is where NASA's Deep Space Network comes in. The DSN dishes can be scheduled to track a particular spacecraft 24 hours a day if it's at a critical point in its mission or otherwise maybe once every couple of days. These tracking runs commence by first pointing a dish at the position the spacecraft is predicted to be. Although the dish's pointing accuracy can be measured within thousandths of a degree, there's still no guarantee the spacecraft will be exactly there, since its solar orbit may be perturbed by a range of factors, but it should be close enough to its predicted location to come within the dish's range.

The dish can then send a standard ranging signal, which is essentially *Where are you now then?* To which the spacecraft replies *I'm over here.*

The spacecraft's exact location in the sky is generally recorded using standard celestial grid coordinates of right ascension and declination. There's a whole other podcast needed to explain how the Deep Space Network recalibrates for parallax error since the Earth is itself shifting around the Sun while we are trying to take these terribly accurate measurements of where the spacecraft is. Essentially, it's done by comparing the spacecraft's position against that of very distant quasars which have virtually no proper motion in the sky.

In any case, just knowing where a spacecraft is in the sky doesn't tell you anything about how far away it is. To accomplish a measurement of distance (which is actually what ranging means), the ranging signal can carry a special ping which is received by the spacecraft and then returned by it to Earth – and the time taken for this ping, which travels at the speed of light, to come back to Earth from the spacecraft can then be used to determine the spacecraft's distance.

Adjustments are made for the signal slowing down as it passes through the atmosphere – and the time taken for each individual spacecraft's electronics to turn a ping around are actually determined before launch – in the Cassini spacecraft's case it's 420 nanoseconds – plus or minus 9 nanoseconds. Needless to say, there's a major focus on accuracy in the spacecraft navigation business.

So, now that you know where it is in the sky and how far away it is we start building up an accurate three dimensional picture of where the spacecraft is in the solar system – or really a four dimensional picture since minor relativistic effects also need to be accounted for. There will always be a certain lag that may be measured in minutes or even hours, between you pressing the start button and the signal reaching the spacecraft to actually fire its engines. If we are serious about trying to get a spacecraft – like say Cassini to fly between Saturn's F and G rings to establish a stable orbit around Saturn – we really do need to understand exactly where it is, and at what time, in the whole space-time continuum.

But are we really ready to fire up the engines yet? Well, no. While your position in space-time is a vital piece of information – fully understanding the initial conditions of your spacecraft before taking an action includes a need to know your spacecraft's velocity – which is technically a measure of speed and direction.

So wanna take a guess at how we measure velocity? We already know we can ping the spacecraft with a radio signal and it will fire a response ping straight back. While that's happening, the spacecraft might be moving at speed in a direction away from Earth – or returning back to Earth. So, guess how we do it? Yep, Doppler effect.

To accurately determine the spacecraft's velocity, a Deep Space Network dish transmits an extremely stable wavelength frequency, which the remote spacecraft then duplicates and sends back to Earth.

This two step process is important since the remote spacecraft cannot carry the ridiculously heavy equipment required to transmit an extremely stable wavelength frequency. All of the three DSN complexes around the world, in Australia, Spain and California, all have a hydrogen maser mediated frequency standard generator sitting in an environmentally controlled room in the basement.

This maser is what determines the extremely stable wavelength frequency in the upload link to the spacecraft. Apparently, the maser's time keeping accuracy is measured within plus or minus one second every 30 million years. Did I mention accuracy is kind of a key issue here?

Anyway, the spacecraft receives this signal and then multiplies the frequency by a constant value (1.175-ish in Cassini's case). This is important, so the return signal won't create an interference pattern with the upload signal – which is quite clever.

So say your space craft is in orbit around Saturn – you might perhaps hear something like *I'm over here* if it's disappearing around the back of the planet – or *I'm over here i*f it's coming back around.

Just a shift of a few hertz within the gigahertz of the wavelength of the download signal can be used to determine the spacecraft's velocity via standard Doppler calculations. Piece of cake. Well, actually I've skipped a whole bunch of more detail on what checks and balances are in place to make sure all the various things that could wrong here, don't go wrong, but phew – you'd want to be a rocket scientist to be able to follow all that stuff.

But finally, we're there. Having accurately determined your spacecraft's position and its pre-existing velocity, it's time to press the start button and fire those rockets to make a minor course correction.

Thanks for listening. Oh sorry, did that seem like a bit of an anti-climax? Well, go and talk to a sailor. Turning the rudder is the easy bit, knowing where you are before you turn it – that's navigation (that was just for dramatic effect. Thanks for listening – really). This is Steve Nerlich from Cheap Astronomy, www.cheapastro.com. Cheap Astronomy offers an educational website where we might be cheap but we can still run rings around Saturn. No ads, no profit, just good science. Bye.