Deep Space Communication

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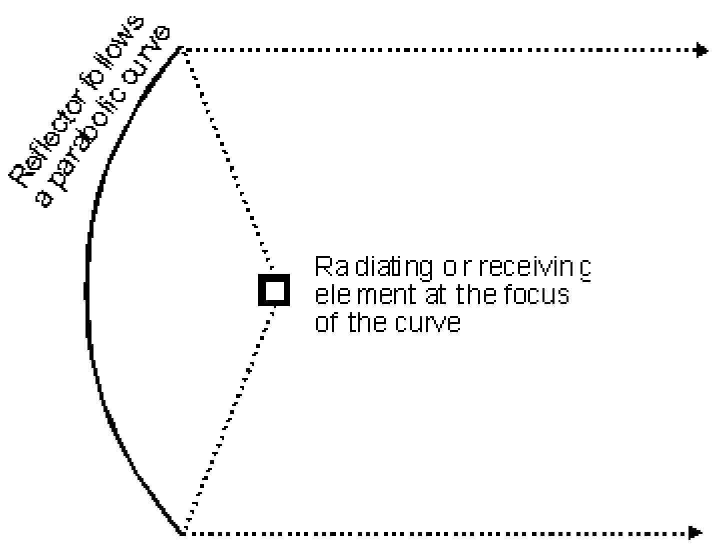
The theory and challenges of deep-space communications

Distance is the main problem in space communications, since the intensity of electromagnetic radiation decreases according to $1/r^2$, that is why signals from deep-space probes are usually very weak when they reach the Earth. In order to receive the faint signal back on Earth large parabolic disc antennas are used. To collect as much as possible of the faint signal the antenna dish must be big. Since the electromagnetic radiation cannot move faster than the speed of light there are considerable time lag introduced in the communications making real time communications impossible. It takes over 5 hours for a signal from earth to reach the orbit of Pluto in the outer part of the solar system. In order to communicate with the Earth the spacecraft must have a free line of sight to the Earth, since radio waves cannot pass through large solid objects such as planets and moons. A space probe orbiting a planet will therefore lose contact with earth every time it gets on the far side of the planet. This means that the spacecraft will not be able to communicate with the Earth at all times. Even if the probe has a free line of sight to the Earth the receiving antenna could be on the wrong side of the Earth, however by using several antennas in different places around the planet that could be solved. The gain of an antenna is a measure of how good the antenna is at focusing the radiated energy. A low gain antenna radiates in a wide angle, while a high gain antenna radiates in a narrow beam.



On spacecraft high gain antennas are used to send scientific measurements at high data rates back to earth as well as receiving steering commands from earth; these antennas are highly directional and require very accurate aiming. Spacecraft are always equipped with at least one low gain antenna often two. These low gain antennas are very important since they can intercept signals from almost any direction, this is useful if the spacecraft gets disoriented and the main high gain antenna doesn’t point towards Earth. If the spacecraft only had a high gain antenna it would then not be able to receive any more instructions from Earth. The low gain antennas are used in these kinds of situations as a backup to receive the appropriate commands that will turn the spacecraft so that the main antenna gets properly aligned to earth again. However, the low gain antenna can only handle a fraction of the data rate compared to the high gain antenna.

Common antennas (e.g. dipole or quarter-wave antennas) send and receive radio waves of a particular polarization, for waves of different polarization the antenna’s sensitivity decreases proportionally to cosine of the angle between the polarization plane of the incoming radiation and the antenna polarization axis [4]. In space this is a problem since the spacecraft antenna might not be aligned properly to the signal polarization. This problem can be solved by transmitting a circular polarized signal from the Earth, e.g. a signal that is a superposition of two plane polarized waves polarized perpendicular to each other, the circular polarized signal will always have a nonzero component along the polarization axis of the antenna.

S-band	1.55 – 5.2 GHz (2.3 GHz)
X-Band	5.2 – 10.9 GHz (8.4 GHz)
K_u-band	12 – 8 GHz
K_a-band	20 – 40 GHz (32 GHz)

Table 1 Commonly used frequency bands for space communication, most common frequencies within parenthesis

Since the signal has to pass through the Earth's atmosphere some limitations are placed on which frequencies that could be used. The ionosphere is almost opaque to some of the lower frequency bands so space communication mainly uses high frequency bands between 2GHz and 40GHz which are less affected by atmospheric disturbances. However at these frequencies one start to get interference from molecular excitations, there are several frequency bands that could not bee used because of this e.g. water has a strong resonance frequency at 22GHz. Water is a severe problem at frequencies above 2GHz, dense clouds, rain and snow can distort and absorb large parts of a transmission [3]. Despite that, frequencies above 2GHz are in common use for space communication, that is because higher frequencies allows for higher data rates, short wavelength radiation can carry much higher data rates than long wave radiation. The space industry is always looking for ways to increase the data rate between Earth and interplanetary probes; low data rate has always been limiting factor during interplanetary communications. On a common interplanetary space probe the low gain antenna usually receives/transmits in the S-band while the high gain antenna receive/transmit in the X-band, however we are now in a transition phase and in the future the high gain antennas will be used with the higher K_a-band.

It is difficult to construct large parabolic antennas for high frequency waves, e.g. K_a-band. The problem arises because of mechanical deformations of the dish, which are mainly caused by gravitational forces and wind, these deformations can easily be of the same order as the wavelength used (wavelength • 1 cm at 30GHz). This could lead to focusing problems or interference in the incoming signal. It is possible to limit the effect of deformations by using an advanced receiver/transmitter that tries to compensate for the dish imperfections. This is one of the reasons why arraying antennas has became so popular, arraying basically means that you connect several smaller antennas and combine their signals to simulate a much bigger antenna. It is easier to (and cheaper) build several small antennas than one large, small antenna dishes (less than 40m) are also much easier to calibrate for use with the K_a-band.

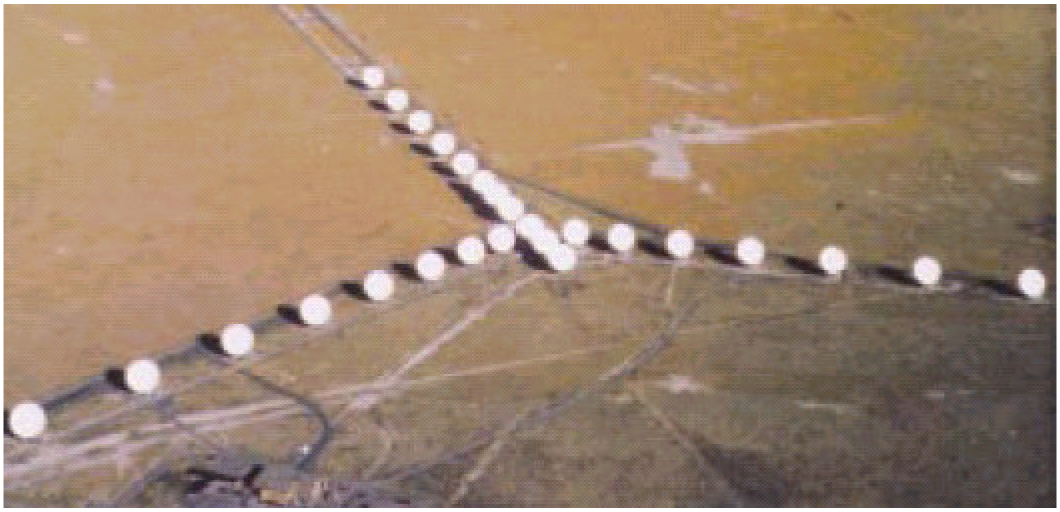


Figure 1 the Very Large Array, New Mexico

Over the last years data rates have increased substantially mainly because of a transition from the X-band to the higher K_a-band, however the data rates are still (always) to low. The new space probes contain scientific instruments that produce much more data than on earlier missions. The communication link with earth is already a bottleneck that limits the use of certain instruments and it seems that the demanded data rate of payloads will continue to increase. In table 2 the data demand of Cassini' s payloads listed. As you could see several of the instruments produce much more data than could be downloaded to Earth in real-time, these instruments could therefore not be turned on for extended periods since the data will pile up and ultimately (quite rapidly) fill Cassini' s internal buffer.

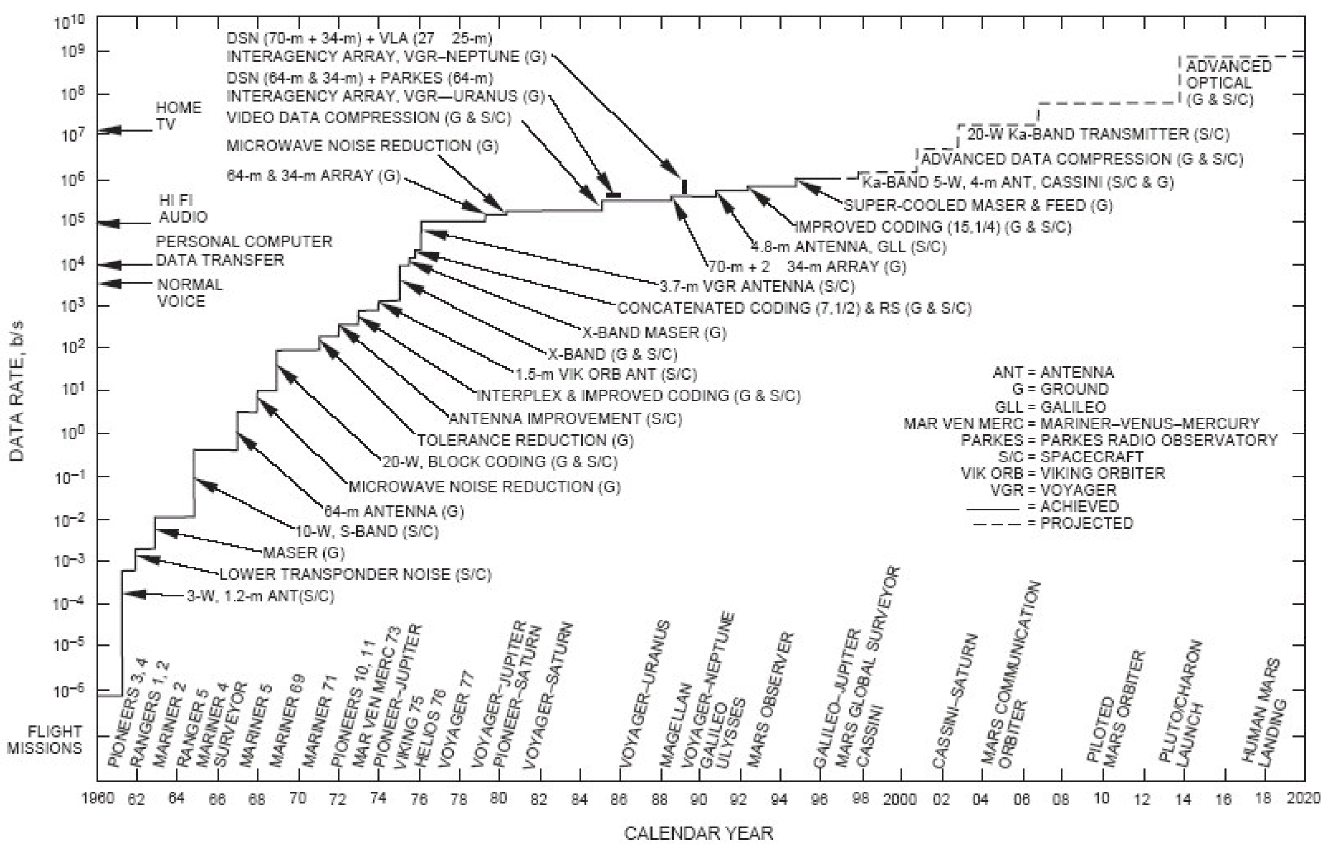
Cassini Science Instrument Data Rates

Science Instrument	Estimated Data Rate Approx. (Kbps)
Cassini Plasma Spectrometer (CAPS)	8.0
Cosmic Dust Analyzer (CDA)	0.5
Composite Infra-Red Spectrometer (CIRS)	6.0
Ion and Neutral Mass Spectrometer (INMS)	1.5
Imaging Science Subsystem (ISS)	365.6
Magnetometer (MAG)	3.6
Magnetospheric Imaging Subsystem (MIMI)	7.0
Cassini RADAR	364.8
Radio and Plasma Wave Science Instrument (RPWS)	0.9
Ultra-Violet Imaging Subsystem (UVIS)	32.1
Visual and Infra-red Mapping Spectrometer (VIMS)	182.8
Total Maximum Downlink Bandwidth	165.9

Table 2 the data requirements of Cassini's payload

Lets take a closer look at the Cassini spacecraft, In the table you can see its scientific payload, to deliver the results back to earth Cassini has one 4m high gain parabolic antenna (X-band) and 2 low gain S-band antenna. The high gain antenna is powered by a 20W transmitter, capable of sending data at 166kbps back to Earth from Saturn. However the uplink from Earth is much slower only about 1kbps, see [1]. The huge difference is due to the fact that the big receiving antennas on Earth are much more sensitive than Cassini's 4m antenna, if Cassini had been equipped with a larger and more sensitive antenna then the difference would have been smaller. It is important to note that the signal sent from Earth is several thousand times stronger than the 20W sent from Cassini.

The technology of space communications are constantly improving as can be seen in the diagram below, that shows the development of the NASA deep space network. The Earth receiving stations are continuously being upgraded or replaced with new technology. Each new space probe contains new and improved technology, the speed increase is not only from antenna and amplifier upgrades but also from the increased use of computers both in ground stations and in space craft. Fast computers are used as digital filters for advanced signal post-processing it also allows for complicated error correction algorithms and data compression all which helps increase the data rate and quality of the received data.



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