

An Introduction to Deep Space Communication

28th June 2015

Nik Ansell
NikAnsell00@gmail.com

Abstract

This paper is aimed at readers with an interest in deep space communication, but do not have any prior knowledge. The content can be used to gain a basic understanding to satisfy a passing interest, and also provide a foundation for further learning as required. Topics covered: Unique challenges of deep space communication, international deep space networks, radio frequency communication fundamentals and deep space antenna design.

Keywords

Deep Space Communication, Deep Space Networks, RF Communication

Introduction

The thirst for knowledge of our universe and its origins seems never-ending. This thirst, combined with the search for extra-terrestrial life or potentially habitable locations for the human race, has led to hundreds of interplanetary space missions over the last 5 decades. These interplanetary missions as described by Dave Doody in his 2009 book have “returned more knowledge about our place in the universe than any human has ever possessed in all the centuries proceeding” (Doody, 2009).

Interplanetary missions have returned detailed images of our solar system, which are impossible to get from earth. For example the famous “Pale Blue Dot” image of earth from a distance of millions of km (NASA, 2006). These images, coupled with other scientific data have provided many thought inspiring discoveries, such as:

- 1,600 km/h winds on Neptune by the Voyager mission (NASA, 2007)
- The discovery of Planet HD 106906b and the relationship with its parent star which potentially challenges current gravitational theories (Chow, 2013)
- The Rosetta space probe found organic carbon based compounds on a comet, which may provide clues to how life on earth began (Kramer, 2015)

The term “Deep Space” is generally used when referring to large distances from earth. The National Aeronautics and Space Administration (NASA) considers deep space to be any distance further than the moon which is roughly 384,000km (Sharp, 2013) (NASA, 2014). However the European Space Agency (ESA) use distances of greater than 2,000,000 km from earth (ESA, 2012). For the purpose of perspective, the NASA and ESA definitions equate the beginning of deep space to distances of 9.6 and 50 times the circumference of the earth respectively, significantly larger than any terrestrial communication links.

During each deep space mission, reliable communication with spacecraft, to send commands or software updates, track location and receive telemetry, images and scientific data is paramount to the success of the mission. This need for reliable deep space communication fuels a constant source of global interest for research and development in the area. In many cases, deep space research and development looks to develop existing technologies further for use in space, for example when pushing the boundaries of radio frequency communication. However, deep space communication, due to its unique challenges constantly pushes communication research and development to its limits.

Unique Challenges of Deep Space Communication

Deep space communication provides some unique communication challenges, which are not normally experienced with typical terrestrial communication.

Huge Distances

Rosetta, the ESA mission to land on comet 67P/Churyumov-Gerasimenko is currently 393,720,000 km from earth. Cassini, the NASA mission launched in 1997 to study Saturn, is currently 1,370,000,000 km from earth. New Horizons, the NASA mission to Pluto and the Kuiper Belt is currently 4,780,000,000 km from earth. However Voyager 2, a NASA spacecraft launched in 1977 to study the outer reaches of our solar system, is currently 16,100,000,000 km from earth and still communicating with NASA ground stations (NASA, 2015).

Constrained by the speed of light, amongst other factors, deep space communication has very high latency, measured in the RTT (Round Trip Time) of light. Rosetta has an RTT of 43.78 minutes, Cassini is 2.54 hours, New Horizons is 8.85 hours and Voyager 2 has an RTT of 1.24 days (NASA, 2015). Even at much closer distances, signals take anywhere from three to fifteen minutes to arrive from Mars (Jackson, 2005).

Data rates at these distances are much lower than typical terrestrial data rates. Data from Rosetta is currently being received at 104.85 Kb/sec, it is received at 20.10 Kb/sec from Cassini, New Horizons data is received at 1.68 Kb/sec and Voyager 2 data is currently received at 160 bytes/sec.

Over time, as more sophisticated equipment generates more data, data rate requirements will continue to increase. In fact, NASA predicts, based on current knowledge of future space experiments, deep space communication capability will need to grow by nearly a factor of 10 during each of the coming three decades (NASA, 2013). The pressure to achieve higher data rates will be further challenged by increasing distances, as spacecraft venture deeper into space.

Spacecraft technology limitations

Most spacecraft use a combination of solar power and radioisotope thermoelectric generators (RTGs). In deep space, where solar power is very weak, RTG's become the primary power source, which generate electricity using the temperature difference between space and the heat expelled by the decaying isotope (NASA, 2014).

However, although RTG's produce power for very long periods of time, they do not produce high volumes of power at the mass typically deployed. Communications equipment on spacecraft must therefore operate at very low power levels. The Voyager spacecraft for example use a maximum of 360 watts for all telecommunications equipment (NASA, 2014).

Long-term reliability, without any physical maintenance is also a critical factor in deep space. Most planetary missions are further than humans can currently travel and tend to be for longer than 10 years. Voyager for example was launched in 1977 and is still active decades later. Unreliability can have a huge impact on a space mission, as seen in 1991 when Galileo's High Gain Antenna (HGA) failed to unfurl. Several attempts were made to free the stuck mechanism over the course of several months, including rapid heating and cooling by rotating it towards and away from the sun, however no attempts to remedy the problem were successful (NASA, 2014). This left the remainder of the mission using only the Low Gain Antenna (LGA) at a significantly lower bandwidth.

The impact of unreliability was also seen in 2011 when the Phobos-Grunt spacecraft launched by the Russian space agency, Roscosmos, failed to engage its thrusters in low earth orbit phase (LEOP) shortly after launch. Control of the spacecraft was completely lost, which resulted in it falling back to earth in January 2012. The cause was reported by Roscosmos to be electronic parts, which were not fully certified for use in space (Friedman, 2012).

As well as being extremely reliable, telecommunications equipment aboard spacecraft must be of a very low mass, due to strict size and weight constraints. Typically the allowance for spacecraft communications equipment is only a few kilograms (NASA, 2013).

Ground Station challenges

At deep space distances, when using traditional radio frequency (RF) communication, the power received at ground stations on earth is very low, requiring highly sensitive equipment. For example when Voyager 2, transmits a 20kW signal from its S-Band transmitter, only 2.47×10^{-22} kW is received by NASA's 70m dish antennas (NASA, 2014). Due to the weak signal being received, very sensitive equipment is required to amplify and process the signal. In ESA's deep space network this includes low noise receivers, which are cooled to -258°C (ESA, 2012).

Equipment must also be manufactured to very high tolerances; this includes dichroic mirrors, which are used to split frequencies. The dichroic mirrors used for RF communication are drilled to the precision of 5-15 microns ($5-15 \times 10^{-6}\text{m}$). The surface of the dish antennas must also be highly accurate. For example the 70m diameter NASA RF antennas have a surface area of 3,850 square meters that must be maintained to an accuracy of one centimetre (NASA, 2015). Fine tolerances must also be factored into the machinery used to position the dishes. The 70m NASA dishes must be able to maintain accuracy to thousandths of a degree per second to remain pointed at spacecraft, while compensating for the Earth's rotation at 0.004 degrees per second (SpaceToday.org, 2015).

Deep Space Networks

Deep space networks currently use large parabolic dish antennas to achieve two-way communication with spacecraft using RF. ESA and NASA have the most sophisticated deep space networks with the widest coverage of space. Both networks consist of three centres, located roughly 120 degrees apart, to provide full 24/7, 360 degree coverage as the earth rotates (SpaceToday.org, 2015). ESA's ESTrack centres are located in New Norcia (Australia), Cebreros (Spain) and Malargüe (Argentina) (ESA, 2012), while NASA has Deep Space Network (DSN) centres in California (USA), Canberra (Australia) and Madrid (Spain) (NASA, 2014).

Each of NASA's DSN stations has one 70m-diameter antenna, one 34m and one 26m antenna (NASA, 2015). ESA's ESTrack centres each have one 35m-diameter antenna (ESA, 2012). In general, smaller antennas are used to track and communicate with spacecraft closer to earth. This is because spacecraft closer to earth require antennas to move more quickly than those at greater distances, and also the stronger signal at shorter distances does not necessitate the use of the larger 70m antennas.

Other notable deep space networks:

- **JAXA** (Japan Aerospace Exploration Agency) Usuda deep space centre with one 64m antenna (JAXA, 2003)
- **ISRO** (Indian Space Research Organisation) Byalau space centre with one 32m antenna, one 18m antenna and one 11m antenna. ISRO also uses ship-borne terminals to track spacecraft in near earth orbit (ISRO, 2012)
- **National Astronomical Observatories of China** centres near Beijing with one 50m antenna, one 40m antenna near Yunnan and 18m antennas in Kashi and Qingdao. Also planned are 35m and 64m antennas in Kashgar and Jiamusi respectively (Renjiang, 2007)
- **Soviet/Russian Deep Space Network**. Little up to date information is available. However the most recent information indicates Ussuriisk in Russia with 70m, 32m and 25m antennas and Yevpatria in Ukraine with one 70m and one 32m antenna, combined with an ADU-1000 array of 8, 16m antennas

RF communication is affected by interference from weather, solar radiation, industrial and household equipment (Crockett, 2015), or other signals such as mobile phones and satellite television. Weather and solar radiation cannot be controlled, however interference from other sources can be minimized by selective placement of the ground stations. To do this, NASA and ESA both have deep space network stations in areas far from dense industry or housing, in some cases areas that are protected by mountains.

Radio Frequency Communication

The electromagnetic radio waves used in deep space RF communication, are part of the same spectrum as infrared, visible light, ultraviolet and X-ray. The radio waves travel in a straight line at around the speed of light, which is roughly 300,000 km per second in space.

The frequency ranges used for communication fit within a spectrum most commonly referred to as the microwave spectrum, which ranges from 1GHz to 300 GHz. This frequency range is broken down into a number of bands, and those typically used for deep space communication are shown below (Australian Space Academy, 2012):

- L-Band: 1.67 – 1.71 GHz MHz
- S-Band: 2.025 – 2.3 GHz
- X-Band: 8-9 GHz
- Ka-Band: 20-30 GHz

Higher frequencies offer higher data rates; however high frequencies are more affected by atmospheric interference, especially frequencies above 30 GHz. This is due in part, to shorter wavelengths being more easily affected by elements such as water droplets (Australian Space Academy, 2012).

A radio wave's power or intensity reduces with distance. The loss in intensity is roughly inversely proportional to the square of the distance, as shown in the formula below. Where I is the intensity (%) of the signal, p is the source point and d is the distance (NASA, 2014).

$$I = \frac{p}{d} ^ 2$$

This formula can be used to estimate, with all other things equal, how theoretical data rates reduce at the average distance of the planets in our universe, as shown below.

- Jupiter 5.2AU
- Saturn 10 AU 1/4 of bandwidth compared to Jupiter
- Uranus 19 AU 1/13 of bandwidth compared to Jupiter
- Neptune 30 AU 1/36 of bandwidth compared to Jupiter

An AU (Astronomical Unit) is the mean distance between the Earth and the Sun, defined by the International Astronomical Union as 149,597,870.700 km (NASA, 2015).

Polarisation & Modulation

Polarisation refers to the movement of the electric and magnetic forces within a radio wave. For example in linear polarization the radio wave moves up and down on a straight plane, like a typical sine wave. In circular polarisation, the radio wave moves in a circular motion, spinning right (Right-hand Circular Polarisation or RCP/RHCP) or left (Left-hand Circular Polarisation or LCP/LHCP). Circular polarisation is favoured over linear polarisation as it provide less loss (SV1BSX, 2011). By using multiple transmitters, antennas can support simultaneous RCP and LCP to achieve higher data rates (NASA, 2014).

A single, steady wave cannot be used to transmit data as there is no way to separate the signal into the zeros and ones required to achieve digital communication. Modulation is the method used to encode zeros and ones within the radio communication. This is generally achieved by sending a carrier signal, which is steady and does not change, and one or more other signals, which differ from the carrier. Demodulation is simply the opposite, converting the received signal back to zeros and ones.

The most common modulation method in use today by NASA (NASA, 2014) and ESA (Hegler et al., 2013) is Binary Phase Shift Keying (BPSK). BPSK sends signals, which are out of phase with each other by a pre-defined number of degrees, the degree offset is referred to as the index (Doody, 2009). Figure 1 illustrates the carrier wave and the modulated out-of-phase wave. Each detected shift is demodulated as a 1 (one) and is combined with the non-shifts as 0 (zeros) to create a bit stream.

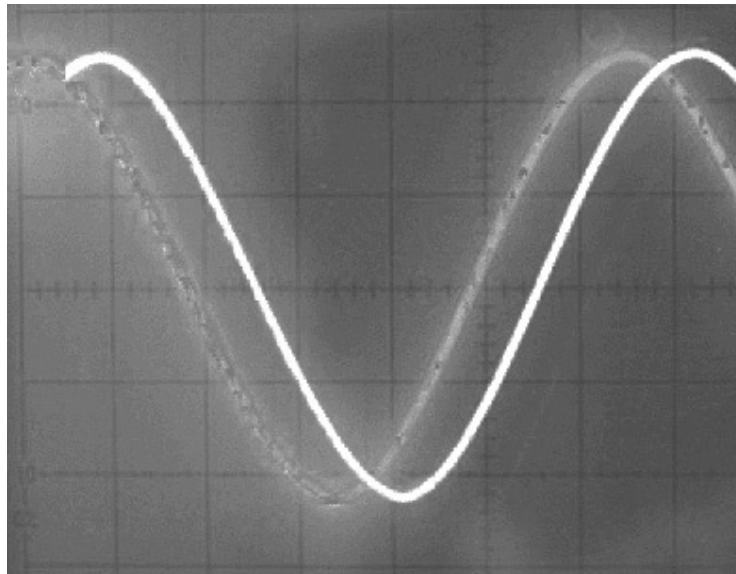


Figure 1. Binary Phase Shift Keying (BPSK) (Doody, 2009)

Error Detection & Correction (EDAC)

In practice, the stream of zeros and ones received after demodulation will have a number of errors, due to noise picked up during the communication. For example, unwanted phase shifts introduced when the signal passes through the earth's atmosphere. The errors will be in the form of zeros interpreted as ones and vice-verse known as bit-flips (Doody, 2009).

In order to achieve near error-free communication, a number of methods have been developed over the last few decades. The most common form of EDAC used in space missions is Forward Error-Correction (FEC). This method sends additional bits (overhead), which can be used to check the consistency of the received data and then rebuild parts of the data stream if required (Doody, 2009) (NASA, 2014).

NASA uses Reed-Solomon and Turbo Code for error detection and correction. Reed-Solomon was introduced as part of the Voyager mission, replacing the previous Golay method. This reduced the number of overhead bits by 20% and reduced the bit-error rate from 5×10^{-3} to 5×10^{-6} , the latter meaning only 5 bits out of one million are incorrect (DECANSO Vol13).

Data Rate & Bandwidth

Although data rate and bandwidth are often interchanged to mean the same thing, they are actually quite different. Data rate or throughput generally refers to the capacity of a network link and is measured in the number of bits per second that can be sent e.g. 2 Mbps (Megabits per second). Bandwidth generally refers to the range of frequencies available to transmit the data and is measured in Hz (Peterson & Davie, 2012).

In addition to the available bandwidth, the overall capacity of a network link is also governed by the quality of the received signal. This quality is most often referred to as the signal to noise ratio, S/N or SNR. The most notable piece of work describing the relationship between capacity, bandwidth and SNR is the Shannon-Hartley Theorem (Peterson & Davie, 2012), typically represented by the formula below.

$$C = W \log_2 (1 + SNR)$$

Where C is the achievable capacity of a channel (in bits per second), W is the bandwidth of the channel (in Hertz), and SNR is the signal-to-noise ratio. SNR is usually expressed as decibels (dB) by the following formula (Peterson & Davie, 2012).

$$10 * \log_{10} (SNR)$$

E.G an SNR of 1000 would normally be expressed as:

$$10 * \log_{10} (1000) = 30dB$$

SNR can, therefore, in conjunction with the number of available frequencies, have a significant effect on the data rates of any given communication. This formula is used to calculate the theoretical maximum capacity of a network link (known as the Shannon-Limit) using a value of zero for SNR. Network and communication engineers and scientists have been continually evolving communication methods and error correction algorithms for decades, attempting to develop communication methods, which are close to the Shannon-Limit.

Deep Space Network Antennas

All deep space network RF antennas operate in roughly the same way, utilizing a Cassegrain radiator design (NASA, 2014) (Wolff, 2015). Radio waves are received by the main parabolic reflector, and then reflected and focused onto the receiving equipment. The receiving equipment then amplifies the signal, before sending onto a signal-processing centre as light down a fibre optic cable (Doody, 2009). The reflector is also used in reverse, to focus the energy into a narrow beam from transmitters when sending data (Doody, 2009).

The newer NASA and ESA ground station antennas are Beam Waveguide (BWG) antennas. BWG antennas deviate from the traditional Cassegrain design by placing the sensitive receiving equipment underneath the dish in a belowground pedestal room, instead of centrally mounting above the reflector as in previous designs. This new placement makes repairs and upgrades much easier, allowing more equipment to be used and provides better thermal control (ESA, 2012) (NASA, 2015).

Each antenna generally supports more than one frequency band using several transmitters and receivers. The received frequencies are separated and directed to the appropriate receivers, using a series of dichroic mirrors. The various mirrors passing some frequencies and blocking others are illustrated by M6 and M7 in Figure 1 (ESA, 2012).

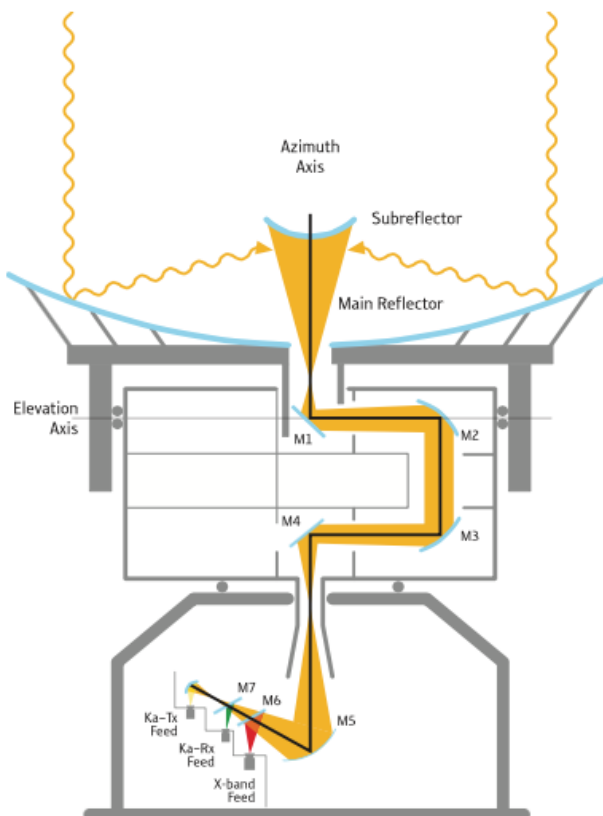


Figure 2. ESA Beam Waveguide Antenna (ESA, 2012)

Antennas built onto spacecraft follow the same Cassegrain design, but on a smaller scale. Spacecraft are normally fitted with multiple antennas, usually one 2-4m diameter High Gain Antenna (HGA) and one or more much smaller Low Gain Antennas (LGA) (NASA, 2014) (ESA, 2014) (Calzolari et al., 1998).

Antennas do not actually amplify power; they simply use the shape of the reflectors to focus the power into a smaller beam. This increases the effective power over the same physical area. Therefore the size of the reflector or aperture directly impacts the gain of the antenna as shown in the formula below. Where G

is the achieved gain, Ae is the effective Aperture area (Aperture diameter multiplied by the calculated antenna efficiency μ) and λ is the wavelength of the radio wave (Doody, 2009).

$$G = \frac{4\pi Ae}{\lambda^2}$$

The performance of an antenna is determined by the difference of the power output to the power input (gain or loss) and typically measured in decibels (dB). The formula to calculate gain or loss is shown below, where dB is the calculated gain, pI is the input power and pO is the output power (TP-Link, 2015).

$$dB = 10 * \log\left(\frac{pO}{pI}\right)$$

Antenna gain is normally stated using a positive or negative value, against a reference 0dB (zero decibels) antenna. For example the Voyager 2 HGA has a gain of 48.2dB within the X-Band frequency range. This HGA can generate a concentrated effective beam of nearly 800,000 watts from a radiated input power of 12 watts (Doody, 2009). These figures are represented in the gain calculation formula below.

$$+48.2dB = 10 * \log\left(\frac{800,000}{12}\right)$$

Traditional Antenna design using the research derived from the formula above, led to the use of larger and larger antennas, up to 70m in the case of the NASA DSN. However these antennas are very expensive to build and maintain. It is simply not feasible to build bigger and bigger antennas to meet the challenge of increasing data rates over increasing distances. This led to researching the use antenna arraying for deep space communication, which combines the signal received by multiple antennas to create a larger effective or synthetic aperture size.

Low Noise Amplifiers

To reduce the introduction of noise into the communication link, low noise amplifiers (LNA's) are used to amplify the received signal. Low noise application is provided using cryogenically cooled ruby crystal Microwave Amplification by Stimulation Emission of Radiation (MASER) units (Amit, 2012) or High Electron Mobility Transistor (HEMT) technology (NASA, 2014) (Doody, 2009). NASA LNAs are typically cooled in the ranges of the boiling point of helium and the boiling point of hydrogen -269°C and -253°C respectively (NASA, 2006). This cooling helps to minimize any noise that would be added by electronic components, as the amount of noise generated by components is directly related to their temperature (Doody, 2009).

MASER technology was first developed in the 1950's based on a concept first introduced by Einstein in 1917. Stimulated emission fires photons of a specific wavelength onto atoms, which has been placed into a high-energy state. This triggers a chain reaction of a quantum physics phenomena called spontaneous emission, where the atoms emit two photons for every one photon received (Stanford, 2015).

High Electron Mobility Transistors (HEMT) are a form of Field Effect Transistor used to amplify the microwave signal using a very thin layer of electrons called a two-dimensional electron gas. HEMTs provide much better amplification than silicon based transistors and are most commonly manufactured from aluminium gallium arsenide (AlGaAs) and gallium arsenide (GaAs), which provides a much higher level of electron mobility than silicon (Mimura, 2002).

LNA Evolution

Due to the high maintenance nature of MASERs, NASA replaced the preamplifiers in their 70m antennas with HEMT technology during 2000 and 2001 (NASA, 2014). In 2006, NASA published a paper indicating

that HEMT technology could provide better amplification at a fraction of the cost and require less cooling (NASA, 2006). This perhaps suggests HEMT technology is overtaking MASER technology.

However, in 2012 a MASER was developed in a laboratory to provide similar levels of low noise amplification at room temperature (Oxborrow et al., 2012). This was achieved using a p-terphenyl crystal doped with pentacene. A room temperature MASER would be significantly cheaper to construct and operate than current MASER and HEMT technology and could see wide scale adoption. Yet this research only provided a MASER that can operate at pulses of about 300 microseconds. This is a significant shortcoming from the continuous operation required for the technology to enter production. Oxborrow hopes his research will lead to significant MASER advancement.

Further Reading

Radio frequency technologies and methods have evolved considerably over the last few decades and have significantly improved data rates and quality. However, as stated, data rate requirements are projected to grow considerably over the coming decades. There are two prominent research areas, which may well address these growing data rate requirements, antenna arraying and optical communication.

Antenna Arraying combines the signals from multiple antennas to create a larger effective aperture. NASA regularly use downlink arrays, and other agencies such as ESA are currently researching their use. However uplink arrays are much more complex and have not yet reached a fully mature state.

Optical communication uses lasers instead of radio waves, for much higher bandwidth over long distances compared to RF technology. However this new technology comes with new and interesting challenges, such as the need for greater accuracy when focussing the very fine laser beam over long distances.

As well as data rate requirements, there is also a growing need to standardize communication protocols and methods as more nodes are launched into Space. The Interplanetary Internet may also be of interest to some readers. This initiative seeks to create a network of interconnected nodes on Earth, in space and also on or orbiting other planets. The development of a new set of protocols is at the heart of research in this area, encompassed in a research area named Disruption Tolerant Networking (DTN).

References

- Amit, G., 2012. *Self-cooling crystal makes room-temperature maser*. [Online] Available at: <http://www.newscientist.com/article/dn22188-selfcooling-crystal-makes-roomtemperature-maser.html#.VTyXdq2qpBc> [Accessed 26 April 2015].
- Australian Space Academy, 2012. *spaceacademy.net.au*. [Online] Available at: <http://www.spaceacademy.net.au/spacelink/radiospace.htm> [Accessed 28 April 2015].
- Calzolari, G.P., Vassallo, E., Benedetto, S. & Montorsi, G., 1998. *Improving Rosetta's Return-Link Margins*. [Online] Available at: <http://www.esa.int/esapub/bulletin/bullet95/CALZOLARI.pdf> [Accessed 27 April 2015].
- Chow, D., 2013. *Space.com*. [Online] Available at: <http://www.space.com/23858-most-distant-alien-planet-discovery-hd106906b.html> [Accessed 22 April 2015].
- Crockett, C., 2015. *Source of puzzling cosmic signals found — in the kitchen*. [Online] Society for Science & the Public Available at: <https://www.sciencenews.org/article/source-puzzling-cosmic-signals-found-kitchen> [Accessed 23 April 2015].
- Doody, D., 2009. *Deep Space Craft An Overview of Interplanetary Flight*. 1st ed. Chichester, UK: Praxis.
- ESA, 2012. *Deep Space Tracking Network*. [Online] ESA Available at: http://www.esa.int/Our_Activities/Operations/Estrack_tracking_stations [Accessed 23 April 2015].
- ESA, 2014. *Rosetta*. [Online] Available at: http://www.esa.int/Our_Activities/Space_Science/Rosetta/The_Rosetta_orbiter [Accessed 27 April 2015].
- Friedman, L.D., 2012. *Phobos-Grunt Failure Report Released*. [Online] Available at: <http://www.planetary.org/blogs/guest-blogs/lou-friedman/3361.html> [Accessed 25 April 2015].
- Hegler, S. et al., 2013. Operation of CONSERT aboard Rosetta during the descent of Philae. *Planetary and Space Science*, 89(1), pp.151-58.
- ISRO, 2012. *Videos Space Science*. [Online] Available at: <http://shiksha.isro.gov.in/marsvideos.aspx> [Accessed 27 April 2015].
- Jackson, J., 2005. *The Interplanetary Internet*. [Online] Available at: <http://spectrum.ieee.org/telecom/internet/the-interplanetary-internet> [Accessed 7 June 2015].
- JAXA, 2003. *Usuda Deep Space Center*. [Online] Available at: <http://global.jaxa.jp/about/centers/udsc/index.html> [Accessed 27 April 2015].
- Kramer, M., 2015. *Strange Comet Discoveries Revealed by Rosetta Spacecraft*. [Online] Available at: <http://www.space.com/28337-rosetta-comet-spacecraft-strange-discoveries.html> [Accessed 22 April 2015].
- Mimura, T., 2002. The Early History of the High Electron Mobility Transistor (HEMT). *Microwave Theory and Techniques*, 50(3), pp.780-82. Available at: <http://www.radio-electronics.com/info/data/semicond/fet-field-effect-transistor/hemt-phemt-transistor.php>.
- NASA, 2006. *Deep Space Network, Cryogenic HEMT LNAs*. [Online] Available at: <http://hdl.handle.net/2014/40245> [Accessed 26 April 2015].
- NASA, 2006. *In Saturns Shadow*. [Online] Available at: <http://www.jpl.nasa.gov/spaceimages/details.php?id=PIA08329> [Accessed 27 April 2015].
- NASA, 2007. *Voyager and interstellar journey*. [Online] Available at: http://www.nasa.gov/mission_pages/voyager/voyagerf-20070820.html [Accessed 22 April 2015].
- NASA, 2013. *Science and Technology*. [Online] Available at: <http://scienceandtechnology.jpl.nasa.gov/research/ResearchTopics/topicdetails/?ID=67> [Accessed 23 April 2015].
- NASA, 2014. *Deep Space Communications*. California, CA, USA: California Institute of Technology.
- NASA, 2014. *Deep Space Communications*. California, CA, USA: California Institute of Technology.
- NASA, 2015. *Astronomical Unit*. [Online] Available at: <http://neo.jpl.nasa.gov/glossary/au.html> [Accessed 28 April 2015].
- NASA, 2015. *Deep Space Network Fact Sheet*. [Online] California Institute of Technology (1.6) Available at: http://www.jpl.nasa.gov/news/fact_sheets/DSN-0105.pdf [Accessed 26 April 2015].

NASA, 2015. *DSN Now*. [Online] Available at: <http://eyes.nasa.gov/dsn/dsn.html> [Accessed 19 April 2015].

Oxborrow, M., Breeze, J.D. & Alford, M.N., 2012. Room-temperature solid-state maser. *Nature*, 488(1), pp.353-56.

Peterson, L.L. & Davie, B.S., 2012. *Computer Networks A Systems Approach*. 5th ed. Burlington, MA, USA: MK.

Renjiang, X., 2007. *Gearing up for Chang'e*. [Online] Available at: <http://www.astronomy.com/news-observing/news/2007/02/gearing%20up%20for%20change> [Accessed 27 April 2015].

Sharp, T., 2013. *How Far is the Moon*. [Online] (1) Available at: <http://www.space.com/18145-how-far-is-the-moon.html> [Accessed 19 April 2015].

SpaceToday.org, 2015. *NASA Deep Space Network*. [Online] Available at: <http://www.spacetoday.org/SolSys/DeepSpaceNetwork/DeepSpaceNetwork.html> [Accessed 25 April 2015].

Stanford, 2015. *Whats is a MASER*. [Online] Available at: <http://einstein.stanford.edu/content/fags/maser.html> [Accessed 26 April 2015].

SV1BSX, 2011. *Antenna Circular Polarisation*. [Online] Available at: <http://sv1bsx.50webs.com/antenna-pol/polarization.html> [Accessed 1 May 2015].

TP-Link, 2015. *Antenna Gain Explained*. [Online] Available at: <http://www.tp-link.ae/article/?faqid=3> [Accessed 27 April 2015].

Wolff, C., 2015. *The Cassegrain Antenna*. [Online] Available at: <http://www.radartutorial.eu/06.antennas/Cassegrain%20Antenna.en.html> [Accessed 27 April 2015].