RTT TECHNOLOGY TOPIC
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Pictures from Pluto - the radio story

This month's technology topic reviews the radio and radar technologies and techniques used to study the planets in our solar system and exoplanets beyond the solar system including the techniques used to communicate with spacecraft and earth and space facing optical and radio telescopes.

We justify this diversion into extra-terrestrial radio on the basis that many of the innovations needed to support these relatively extreme communication applications are relevant to 5G design and development.

The image processing and RF signal processing and data handling requirements of these systems are similarly extreme and provide a testing ground for future terrestrial radio and radio processing technologies.

The failure of an RF or digital component in space compared with the launch cost of a spacecraft or satellite means that component and system reliability needs to be achieved almost regardless of cost. Therefore although unit numbers are small, civilian and military space components and space systems command significant R and D spending. This translates into component and system innovation.

There are therefore a number of useful touch points between space radio communication and observation systems and 5G terrestrial radio.

Planets in the news – pictures from Pluto

The New Horizons piano sized spacecraft was launched in 2006 with the mission to explore Pluto, the most distant planet in our solar system.[1]

There are seven instruments on board, three optical instruments including a high resolution camera, two plasma instruments for measuring charged particle emissions, a dust sensor and a radio receiver/radiometer to measure the radiant flux power of electromagnetic radiation. The payload consumes 28 watts.[2]

The instruments are optimized for the low light levels and the cold of Pluto and the Kuiper Belt and are capable of measuring the geology of Pluto, the surface composition and temperature, atmospheric pressure and the structure of the atmosphere reaching out 10,000 kilometres to Charon, Pluto's geostationary moon.

Pictures from Pluto travel 4.8 billion kilometres and take 4.5 hours to arrive on earth via three NASA 70 metre diameter deep space dishes[3] in California, Madrid and Canberra. The three dishes combined together provide sufficient link budget to support the telemetry and communication needs of the mission which at that distance means at best about one kilobit per second.

The images have 1024 pixels digitized as a 12 bit number. Loss less compression reduces the file size to 2.5 Megabits which means that it takes 42 minutes to get one image back to Earth.

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[1] https://www.nasa.gov/mission_pages/newhorizons/main/index.html
[2] http://pluto.jhuapl.edu/Mission/Spacecraft/Payload.php
[3] http://deepspace.jpl.nasa.gov/

Communication sessions via the NASA deep space network last eight hours with generally one session bookable in a 24 hour period. This theoretically means eight images in a session or per day but the spacecraft has other communication needs including housekeeping and outputs from the other instruments.

There are ways of increasing throughput. The spacecraft has two travelling wave tube amplifiers connected to a 2.4 metre dish. The second amplifier was there to provide redundancy but the two amplifiers can be made to work together with one signal with left handed polarisation and one signal with right handed polarization. This increases the data rate by 1.9 times but doubles the power requirement.

After ten years, the nuclear power source cannot generate enough power to run both amplifiers simultaneously. This can only be done by shutting down the guidance system which means putting the spacecraft into a spin to keep its pointing stable. This uses up the hydrazine needed for orbit corrections but can be worthwhile for short periods.

Other missions supported from the Deep Space Network

The deep space network simultaneously needs to support at least thirty other spacecraft flying through space including Voyager 1 launched in 1977 which is now 40 billion kilometres away, a 36 hour radio round trip.

In August 2012 Voyager 1 made the historic transition to the inter stellar medium and is now part of the planned Voyager Interstellar Mission. Voyager 2, launched just before Voyager 1, took a different route through the solar system and is currently 15.35 billion km from the sun.

The two spacecraft passed Jupiter and Saturn, discovering active volcanoes on Jupiter's moon and previously unknown properties of Saturn's rings. Voyager 2 went on to explore Uranus and Neptune and is still the only spacecraft to have visited those planets.

Other spacecraft include Rosetta and Philae clinging precariously to Comet 67P/Churyumov-Gerasimenko, 500 million kilometres from earth following a ten year journey of six billion kilometres. There is therefore substantial competition for a limited amount of deep space communications bandwidth.

Spectrum for space

Most spacecraft use a portion of X-band at 8.4-8.5GHz, set aside globally for deep space communications. Because the signals coming back to Earth are weak, agencies such as NASA allocate dedicated frequency bands to avoid interference from terrestrial sources.

Increasing amounts of terrestrial noise and a need to improve the sensitivity of near space and deep space receivers mean that space agencies are lobbying for higher frequencies around 32GHz to be made available.

Planets and their Auroras and the search for habitable planets

The closest planets to Earth are either Venus or Mars. In 2003, Mars made its closest approach to Earth in almost 60,000 years at 55 million kilometres. The average distance is 225 million kilometres, a 22 minute trip by radio.

There are a range of ways of studying the planets in our solar system and the exoplanets in our galaxy.

The bulk of atmospheric observations to date have been accomplished by the transit method. When a planet is in front of a star, some of the starlight passes through the planet's atmosphere, picking up atmospheric spectroscopic features.

The Very Large Array radio telescope in Albuquerque, New Mexico recently discovered an aurora on the exoplanet LSRJ 1835 18 light years away in the Lyra constellation.[4] The radio observations were correlated against images from the Hale optical telescope in Paloma in the USA and Keck Observatory in Hawaii. The aurora is red in colour due to the interaction of charged particles with hydrogen in the atmosphere. Technically the object is too large to be a planet and too small to be a sun and is therefore described as a Brown dwarf but the general consensus seems to be emerging that it behaves more like an oversize planet.

The NASA Maven mission[5] has observed an aurora on Mars which penetrates deep into the Martian atmosphere due to Mars having lost its magnetic field some billions of years ago.

While we are now more or less sure that there is no life on Mars, astro scientists are looking further afield. NASA's Kepler mission[6] recently confirmed the first near-Earth-size exoplanet Kepler 425b in the "habitable zone" around a sun-like star. Kepler 425b has spent six billion years in the habitable zone of its star, rather longer than earth and therefore a good candidate for extra-terrestrial life. It is located 1400 light years away in the Cygnus constellation and was identified by correlating optical and radio measurements from the McDonald Observatory in Texas, the Fred Lawrence Whipple Observatory on Mount Hopkins in Arizona and the Keck Observatory in Hawaii.

There are now over 1000 planets that have been separately identified outside of the solar system despite their low radio brightness when compared to their adjacent stars and over 4000 candidate 'possible planets' that need to be verified. Nine of these planets are similar in size to Earth and are in an orbit that is similar in terms of distance from the Sun. The challenge will be to find ways of identifying bio signature gases on the planets to provide an indication of potential life. This will require another generation of optical and radio telescopes.

Radio search for extra-terrestrial life

The radio search for life is being partly financed by Yuri Milner, a theoretical physicist and internet entrepreneur. Born in 1961 and named after Yuri Gagarin (the first man in space), Yuri Milner has paid for thousands of hours of time on the Green Banks Radio Telescope in West Virginia and the Parkes Telescope in New South Wales. The radio measurements will be correlated with laser emission measurements from the Lick observatory in California.[7] The combined measurements are calculated to be capable of detecting a 100 watt signal 25 trillion miles away. The 'Breakthrough Listen' project[8] has a $100 million dollar budget. The radio measurements will be 50 times more sensitive and cover ten times more sky than previous projects like SETI but will use some of the same analysis methods pioneered by SET including the use of nine million volunteer computers.[9] The search will cover the nearest 1000 stars and will be the first project to scan the whole of the 1-10 GHz frequency band, the wavelength window considered to be the most productive for discovering extra-terrestrial life.

Particular frequencies of interest are hydrogen atoms at 1420 MHz and hydroxyl molecules at four frequencies between 1612 and 1720 MHz. Collectively the range of frequencies between 1420 and 1720 MHz is called The Water Hole.

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[4] http://www.bbc.co.uk/news/science-environment-33711161

[5] http://mars.nasa.gov/maven/

[6] http://kepler.nasa.gov/

[7] http://astronomynow.com/2015/07/21/lick-observatory-joins-search-for-intelligent-life-in-the-universe/

[8] http://phys.org/news/2015-07-aliens-unveil-secrets-universe.html

[9] http://www.seti.org/

These narrow emission lines produced at characteristic frequencies by atoms and molecules are measured separately from continuum radiation,[10] the broadband radiation emitted in the radio part of the spectrum by celestial objects. Its intensity (brightness temperature) varies relatively slowly as a function of wavelength (or frequency).

Specific frequencies are assigned for spectral line narrow band observation and for continuum observation, solar wind observation, solar observation and pulsar observation via very long base line interferometers.

Narrow band frequency resonant spectral line observation is the intellectual feed stock for astro chemists. Most of the other observations address the mechanics of the Universe. The spectral lines red shift over cosmological distances but can be recognised by their relative wavelength relationship. This allows for precision dating and distance calculation and can be correlated with the shift of wideband cosmic background radiation, originally white light, shifted down to RF wavelengths.

Planets sometimes have particularly interesting transmissions at awkward wavelengths for terrestrial observation. Jupiter's most interesting radiation for example is between 15 and 30 MHz.

Radio astronomy bands are designated to provide protection against radio interference from any unwanted source. The allocations do not mean that other wavelengths cannot be used but they will not have regulatory protection. The frequency allocations in the European Union and their present uses are listed below[11]

Sub 1 GHz Space Observation Bands

Frequency - MHz	**Band**	**Application**
13.36- 13.41 MHz	HF	
25.55-25.67 MHz	HF	
37.5-38.25 MHz	VHF	Continuum observations
73-74.6 MHz	VHF	Solar Wind Observations Continuum Observations
150.05-153 MHz	VHF	Solar Observations Continuum Observations Pulsar Observations
322-328.6 MHz	UHF	Continuum Observations VLBI
406.1-410 MHz	UHF	Continuum Observations Pulsar Observations
608-614 MHz	UHF	Continuum Observations VLBI

L Band Space Observation Bands

Frequency	**Band**	**Application**	**Spectral Line**
1400-1427 MHz	L Band	Spectral line observations	21 cm hydrogen line
1660-1660.5 MHz	L Band	VLBI	
1660.5-1668.4 MHz	L Band	VLBI Spectrum line observations Continuum	

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[10] http://www.hartrao.ac.za/continuum/

[11] http://www.ukaranet.org.uk/basics/frequency_allocation.htm

		Observations	
1668.4-1670 MHz	L Band		
1718-1722.2 MHz	L Band		

S band Space Observation Bands

Frequency- MHz	Band	Application
2655-2690 MHz	S band	Continuum observations
2690-2700 MHz	S band	
3260-3267 MHz	S band	
3332-3339 MHz	S band	
3345.8-3352.5 MHz	S band	

C Band Space Observation Bands

Frequency- MHz	Band	Application
4800-4990 MHz	C Band	Continuum Observations
4990-5000 MHz	C Band	Continuum Observations VLBI
5000-5030 MHz	C Band	VLBI

X Band Space Observation Bands

Frequency- GHz	Band	Application
10.6-10.68 GHz	X Band	Continuum Measurements VLBI
10.68-10.7 GHz	X Band	Continuum Measurements VLBI

Ku Band Space Observation Bands

Frequency- GHz	Band	Application
14.47-14.5 GHz	Ku Band	Spectral line observations VLBI
15.2-15.35 GHz	Ku Band	VLBI
15.35 -15.4 GHz	Ku Band	Continuum Observations VLBI

Ka-band Space Observation Bands

Frequency GHz	Band	Application	Spectral Line
22.01-22.21 GHz	Ka Band	Spectral line observations	Water line
22.21-22.5 GHz	Ka Band	Spectral line observations	Water line
22.91-22.86 GHz	Ka Band	Spectral line observations	Methyl Formate Ammonia
23.07-23.12 GHz	Ka Band	Spectral line observations	
23.6-24 GHz	Ka Band	Spectral line observations Continuum Observations	Ammonia Line
31.2-31.3 GHz	Ka Band	Continuum Observations	

31.3-31.5 GHz	Ka Band	Continuum Observations	
31.5-31.8 GHz	Ka Band	Continuum Observations	
36.43-36.5 GHz	Ka Band	Spectral line observations	Hydrogen Cyanide Hydroxil

Q, V and W Band Space Observation Bands

Frequency GHz	Band	Application	Spectral Line
42.5-43.5 GHz	Q Band	Spectral line observations	Silicon Monoxide +other lines
48.94-49.04 GHz	Q Band	Spectral line observations	Carbon Monosulphide
51.4-54.25 GHz	V Band		
58.2-59 GHz	V Band		
72.77-72.91 GHz	V Band	Spectral line observations	Formaldehyde
86-92 GHz	W Band	Spectral line observations Continuum Observations	
92-94 GHz	W Band	Spectral line observations	Diazenylium +other lines
95-100 GHz	W Band	Spectral line observations Continuum Observations	

Co-existence issues – terrestrial radio telescopes and terrestrial radio systems

From the above it is clear that coexistence between terrestrial radio systems and terrestrial radio telescope receivers has to be managed both in the metre band (300 MHz to 3 GHz), centimetre band (3-30 GHz) and millimetre band (30 to 300 GHz).

Fortuitously and deliberately, radio telescopes tend to be situated in areas of low RF activity. Not a lot of people use their cell phones in the Atacama Desert in Northern Chile at 5000 metres. However some radio telescopes have to be in populated areas to meet required and specific aperture requirements. The Deep Space installation in Madrid is an example.

Space antennas face upwards most of the time but local RF power can still have a desensitization effect particularly at low pointing angles. Interference from Mobile Satellite Systems also has to be managed and mitigated. MSS satellites know where they are and what they need to avoid and can turn spot beams on and off as required. Terrestrial mobile handsets however could be anywhere and cover a swathe of spectrum directly adjacent to radio observation spectrum.

Each new generation of radio telescope is required to have improved sensitivity over a wider channel bandwidth over a wider pass band. Contemporary radio telescopes have channel bandwidths>500MHz and pass bands of many tens of GHz. Large amounts of money are spent on highly efficient RF front ends often cryogenically cooled to minimize noise floors. This increases the vulnerability of these systems to terrestrial and extra-terrestrial interference.

In all three ITU regions there are submissions to allocate additional protected spectrum for next generation near space and deep space radio observation systems.

These future requirements are being arbitrated within the ITU[12] and include designated frequency bands for radio astronomical measurement, protection of radio astronomy from adjacent channel interference and spurious emission, protection of radio astronomy services in frequency bands shared with other services, protection from unwanted emissions from wideband digital modulation, protection of radio astronomy measurements above 60 GHz from ground based interference, radio quiet protection for the L2 Sun/earth Lagrange point, sharing studies for frequencies between 10 Terahertz and 1000 Terahertz, compatibility with non-geostationary satellite systems including MEO and LEO communication satellites, mutual planning between earth exploration satellite services and radio astronomy in the 94 GHz and 130 GHz bands and preferred bands for radio astronomy between 1 and 3 THz.

The spectral line frequencies, for example the hydrogen line at 21 cm/1400-1427 MHz need to accommodate the Doppler shift introduced when the spectral line is viewed from distant galaxies, a radial velocity shift of up to 100 kilometres per second.

The hydrogen line has been observed red shifted to 500 MHz and some of the most abundant molecules have been detected in galaxies with velocities of up to 50,000 kilometres per second which translates into a 17% frequency reduction.

There are more than 3000 spectral lines outside the allocated bands which radio astronomers can observe as far as spectrum sharing and interference allows. The general point to make is that radio astronomy bandwidth requirements are increasing over time and there is a growing appetite for higher protection ratios to support deep space observation.

Radar and the scaling of the solar system

Radar started to be used after the Second World War to scale the solar system.

The first radar echo from the moon was achieved in 1946 by Zoltan Bay, a Hungarian scientist.[13] The combination of pulse delay and Doppler shift provided the basis for mapping the Moon. The Lovell radar achieved an echo from Venus in 1961 and provided the basis for measuring delay introduced by the atmosphere of the planet, the atmosphere of earth and gravitational effects.

In 1988 the S band (2380 MHz/ 12.6 cm) radar transmitter and 305 metre dish at the Arecibo Observatory in Puerto Rico mapped the Maxwell Montes region of Venus with a horizontal resolution of 2 kilometres. The mountain is 11 kilometres above the surrounding plain.

Craters near the North Pole of Mercury were mapped using delay and Doppler at a resolution of about 15 kilometres.

Terrestrially based radar beyond the solar system is not practical. However radar on board spacecraft visiting planets and other objects can be used to examine the density of dust clouds, to calculate local distances and can be used for terrain mapping and surface and sub surface examination.

Distances beyond the outer edges of the solar system are calculated by optical and radio brightness and red shift. Once you get away from the immediate group of stars surrounding our solar system, a bigger measurement base is needed. The Universe is scaled in parsecs, a unit of *distance* equivalent to 3.26 light years. A Parsec is determined geometrically using the size of the

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[12] https://www.itu.int/rec/R-REC-RA/en

[13] http://history.nasa.gov/SP-4218/ch1.htm

orbit of the Earth around the sun, and the apparent motion of nearby stars. A kiloparsec is 1000 parsecs.

In space, a large rocky body in orbit about the Sun is referred to as an asteroid or minor planet. Smaller particles in orbit about the Sun are referred to as meteoroids. Once a meteoroid enters the Earth's atmosphere and vaporizes, it becomes a meteor, or shooting star. Asteroids and comets have a similar origin and are both made from material left over from the formation of the solar system 4.5 billion years ago. Asteroids are made up of metals and rock. Comets like 57P presently hosting Philae and Rosetta are made of ice, dust, rock and organic compounds. The ice melts and vaporizes as comets get closer to the sun. Most asteroids are in the asteroid belt between the orbits of Mars and Jupiter. Comets mainly come from the outer edges of the solar system including the Kuiper Belt near Pluto or the Oort Cloud[14] 20 trillion kilometres from the Sun.

Near-**E**arth **O**bjects (NEOs) are comets and asteroids that have been deflected by the gravitational attraction of nearby planets into orbits that bring them close to Earth. The Near Earth Object (NEO) Programme is a NASA programme detecting potentially hazardous asteroids and comets that could approach the Earth. 90% of the near-Earth objects larger than one kilometre have been discovered (about 900 objects) and the hunt is now on for objects larger than 140 metres. A total of 1600 objects are classified as potentially hazardous.

A meteor impact off the coast of the Yucatan Peninsula in Mexico is assumed to be the probable cause of the extinction of the dinosaurs 65 million years ago. A 150 metre asteroid exploded 5 to 10 kilometres above the Tunguska region in Russia in 1908 causing an air burst that flattened trees and killed animals over an area of several square kilometres. The 20 metre meteor that landed in Russia in 2013[15] caused over 1000 injuries, including cuts from glass, concussion, retinal burns and sunburn.

The NEO system is being upgraded to a 1 megawatt 12.6 cm radar system with a back end that supports significantly more sophisticated signal processing than its predecessors. More bandwidth and an increase in receiver bandwidth and sensitivity together with a 10 MHz sampling rate and 20 MHz decoder should deliver an order of 40 times improvement in sensitivity.[16]

Summary

Over the past sixty years terrestrial and space based radar has provided the basis for scaling the solar system, helped to map the terrain and surface and the below surface structure of the nine planets in our solar system.

In parallel radio systems have evolved to bring us pictures from spacecraft either orbiting or landing on the planets in our solar system. These are supported from the NASA Deep Space network providing communications to spacecraft at distances up to 40 billion kilometres from earth. Radio telescopes are also being used to search for extra-terrestrial life.

The quest for every more powerful wide band wide channel bandwidth radio telescopes suggests that additional dedicated spectrum may be needed in the future in the metre, centimetre and millimetre bands.

This implies a need to manage co-existence between terrestrial radio and wide band radio astronomy observations (continuum measurements and VLBI measurements), coexistence of terrestrial radio with narrow band spectral line detection and coexistence of wide band and narrow band astronomy with LEO and MEO mobile satellite(MSS) systems including L band and S band

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[14] http://solarsystem.nasa.gov/planets/profile.cfm?Object=KBOs&Display=OverviewLong
[15] http://www.bbc.co.uk/news/world-europe-21468116
[16] http://echo.jpl.nasa.gov/~lance/radar.small.body.mission.targets.html

MSS. Coexistence issues in the sub millimetre band from 300 GHz to 3 Terahertz will also need to be addressed.

The enabling technologies of space based and terrestrially based radio astronomy include highly efficient RF centimetre and millimetre band receivers coupled to multiple antennas with multiple low noise receive chains and associated digital signal processing and digital image processing techniques. Digital processing and correlation across multiple inputs and multiple frequencies provides the basis for interference and noise cancellation in both the optical and RF domain including the mitigation of narrow band RF interference.

Radio measurements are correlated across the whole EMC spectrum including spaced based gamma ray measurements used to research high energy radiation including radiation from pulsars (due to gamma rays not being affected by the large scale magnetic field of the galaxy).

This requires data processing, correlation and data analysis techniques that are significantly more complex than present 4G and proposed 5G mobile broadband network requirements.

Next generation radio astronomy and space radar systems are dependent on a range of enabling component and system technologies that are in turn directly useful to terrestrial radio system design.

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