Remote sensing across the spectrum

γ-rays	X-rays	UV	Visible	IR	Microwave	Radio

Wavelength: 0.01 nm 30 nm 400 nm 700 nm 1000 µm 100 mm

- Remote sensing covers the EM spectrum
  - **passive sensing** – detection of what is naturally emitted
    - main source of emission is blackbody radiation (from ground or Sun)
    - on planets/moons without atmosphere γ-rays can be detected in orbit from radioactivity in rocks
  - **active sensing** involves generation of signal by satellite (or plane) and observation of reflected signal

1

Microwaves

Common microwave band designations

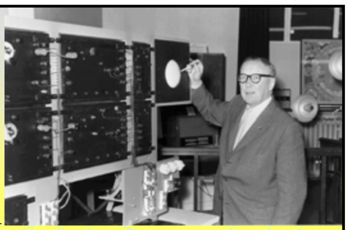
Band	Frequencies (GHz)
S	2 – 4
C	4 – 8
X	8 – 12
K_u	12 – 18
K	18 – 27
Ka	27 - 40
Q	36 - 46
V	46-56
W	56-100

- Wavelength: 1 mm – 100 mm
  - corresponding frequencies 3 GHz – 300 GHz
    - some people take 1 GHz to 100 GHz
  - spectrum divided into 'bands' by convention
    - unfortunately, not everyone agrees on band boundaries
  - (microwave cookers: ~2 → 3 GHz, in S Band)

2

Radar

- **R**adio **d**etection **a**nd **r**anging
- Developed for military purposes by 'famous NE man' Watson-Watt from 1935



'Father of Radar': Sir Robert Watson-Watt (1892 – 1973)
Courtesy: http://www.wdc.rl.ac.uk/ionosondes/history/watsonwatt.gif

- All early work was aimed at how far away objects were
- Radar is an example of **active** remote sensing

http://www.linuxgazette.com/issue42/gm/images/radar.jpg

3

Distance detection

Meterololgical radar
http://www.bom.gov.au/reguser/by_prod/radar/radarexp.shtml

http://badc.nerc.ac.uk/graphics/logos/small/dish.gif

- Pulse sent: takes time t to return
- Distance away of reflection is $d = v \times t/2$
  - v is speed of propagation of pulse ≈ c
    - e.g. $t = 20\ \mu s$, $d = 3{\times}10^8 \times 20{\times}10^{-6}/2 = 3{\times}10^3$ m ≡ 3 km
- If the object is moving with speed s away from the radar, the return frequency, f', is less than the sending frequency, f
  - $f' = f\,(1\text{-}s/v)$
  - this effect is called the Doppler shift
    - e.g. if f = 10 GHz and $f - f'$ = 1 kHz, then s = 30 ms^{-1}

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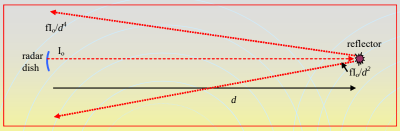
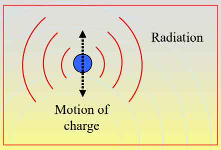
Returning signal falls off as $1/d^4$



- Signal radiated with intensity I_o at unit distance
- Signal reaching a particular object $I = I_0/d^2$
- Signal re-radiated = $f\,I_0/d^2$, f is the fraction reflected
- Signal received back at transmitter = $(fI_o/d^2)/d^2 = fI_o/d^4$
  - *e.g. how much is the signal reduced when the reflecting object is 3 km away instead of 1 km?*
    - *answer: the signal is reduced to $1/3^4$ = 1/81 =0.0124*
  - *A sideways looking radar detects similar objects at distances from 10 km to 100 km. How much weaker are the signals from 100 km compared with those from 10 km?*
    - *answer: weaker by a factor of $(100/10)^4 = 10^4$*

5

The basis of electromagnetic radiation



- Electromagnetic radiation is produced by an oscillating electric charge
  - the radiation is at the same frequency as the oscillation
- Since currents are moving charges, to generate a radio wave, you need to generate an oscillating electric current at the desired frequency

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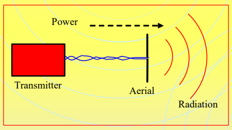
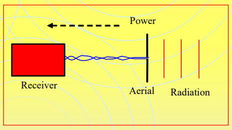
Transmitting & receiving

- An aerial is a device that converts electrical power to EM radiation and vice-versa





- with a good aerial, there is no reflection of power at the aerial
- a given aerial is as good at receiving as it is at transmitting

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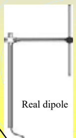
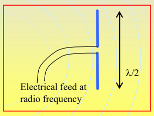
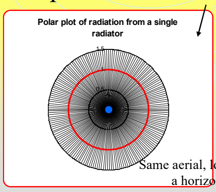
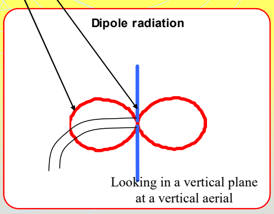
Aerial considerations

- Efficient aerials are at least half-a-wavelength (λ/2) long
- Consider a 'half-wave dipole'
- In plane containing the aerial
  - no radiation parallel to aerial
  - maximum radiation ⊥ aerial
- In plane ⊥ to aerial





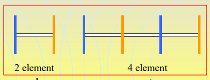


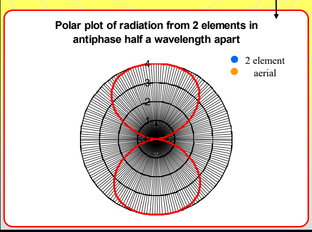


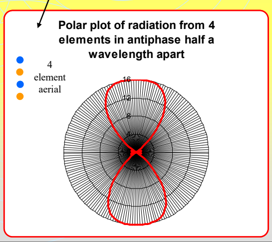
8

Making the aerial more directional

- Adding more elements side by side gives a vertical aerial directionality in a horizontal plane



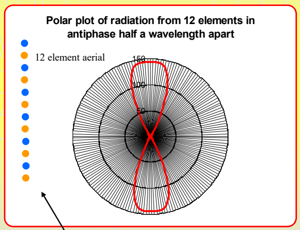


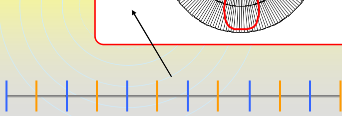


9

Many elements improve an aerial's directionality

- Calculations here are for a 12-element array
- Such an aerial is called a **phased array**





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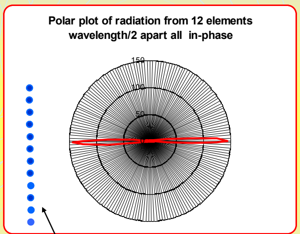
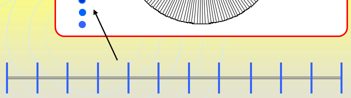
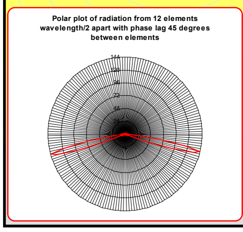
Changing the phase of a phased array

- In the plot on the right, all the elements are in-phase
  - the direction of maximum transmission has changed by 90º
  - making less drastic changes enables the directional response of the aerial to be changed







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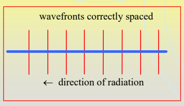
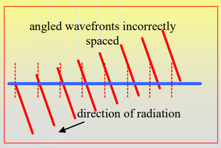
Yagis and parasitic elements

- Receiving aerials like this are called **yagis**
  - they usually have one signal element and the rest are *parasitic* elements that act in sympathy
  - the parasitic elements re-radiate so that they re-inforce the signal at the active element
  - this does not happen for reception of angled waves





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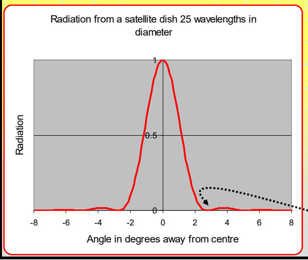
Parabolic reflectors

- Microwaves have a sufficiently small wavelength that they usually use parabolic or spherical reflectors fed at the focal point



- *If the signal falls by 50% 1.5º away from the axis of the dish, how accurately must the dish be mounted to keep the signal within 50% of the maximum?*
  - Answer: within 1.5º of the direction of the satellite
- If the diameter of the dish is *d*, then the signal falls to zero at an angle ~1.22λ/*d* **(in radians)**

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A really big dish!

- The 76 m wide dish of the Lovell Telescope at Jodrell Bank

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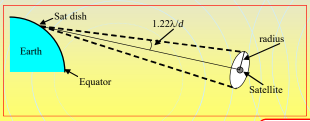
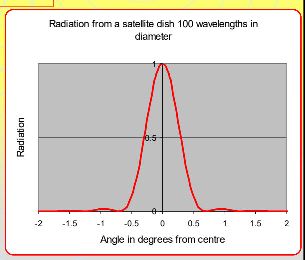
The bigger the dish, the more directive it is



http://www.erh.noaa.gov/er/mhx/tour/dish.html

- A satellite dish is 100 wavelengths in diameter at 10 GHz
  - *how big is it?*
    - λ = 3 cm, therefore *d* = 3 m
  - *what radius of circle does it 'see' at the distance of a geostationary satellite 40,000 km away*
    - λ/*d* = 1/100
    - angular radius is 1.22 λ/*d* = 0.0122 rad (≡ 0.7º)
    - linear radius = 40,000×0.0122 = 488 km



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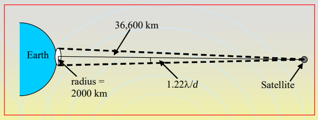
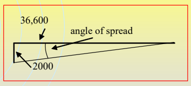
Satellite coverage works the same way



Japanese GMS

- *A satellite operator wants their signal to cover an area of radius 2000 km below their geostationary satellite. How many wavelengths diameter does their satellite dish need to be?*
  - tan (angle of spread) = 2000/36600
  - angle of spread = 3.13º = 3.13 × π/180 radians = 0.0546 radians (also = 2000/36600)
  - therefore 1.22λ/*d* = 0.0546, giving *d*/λ = 22.4
    - at 10 GHz this is 67 cm, a manageable size
    - at mobile phone frequency of 1.5 GHz, the size needed would be 4.5 m



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A modern communications satellite

Courtesy: EADS Astrium

- Inmarsat-4
  - a modern communications satellite providing broad-band services across continents
- 3 similar geostationary satellites
  - £200 million each
  - mainly built in the UK by EADS Astrium
  - 7 m high, 6 tonnes weight, 45 m wingspan of solar panels, 13 year anticipated mission life

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Relative performance is measured in dB

Comms satellite coverage from 13º E
http://rrsat.com/digital_platforms.htm

- dB stands for **decibel**
- dB measures the ratio of two powers P_1 and P_2
- Measure in dB = $10\log_{10}(P_1/P_2)$
  - P_2 may be a standard power, such as 1W
  - e.g. $P_1/P_2 = 10$, dB = 10 × 1 = 10
  - e.g. $P_1/P_2 = 100$, dB = 10 × 2 = 20
    - remember that $x = 10^{(\log_{10} x)}$
- Illustration shows how signal strengths are plotted

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Sending from GEO and LEO

- **Geo**stationary satellite may be 40,000 km from target area
- **L**ow **E**arth **O**rbit (LEO) satellites variable, say 800 km
- Signals at different distances from transmitter obey **inverse square law**
  - power received P ∝ $1/r^2$
  - $P_{LEO}/P_{GEO} = r^2_{GEO}/r^2_{LEO} = 40000^2/800^2 = 50^2 =$ 2500
  - therefore dB gain from LEO is = 34 dB

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Radar Imaging

- Black body radiation
  - produced by random motion of atoms (heat)
  - at long wavelengths, energy density ∝ T/λ^4
  - 10 mm microwaves are 10^4 longer in wavelength than waves where maximum emission takes place (~1 μm for T = 300 K)
  - Earth at microwave frequencies is very, very dark
    - radio receivers tend to be tuned – not broad-band
- Microwave imaging requires illumination by man-made sources
  - satellites may use several kW transmitter

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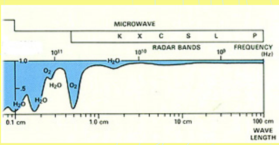
Atmospheric transmission

- Why microwaves?
  - atmosphere is transparent to microwaves



Sketch from http://rst.gsfc.nasa.gov/Intro/Part2_4.html

  - Rain, fog, haze, dust are all due to particles with size << wavelength of microwaves used for terrain imaging (typically C band λ ~ 5 cm)
  - Landscape images can be made, whatever the weather, day or night and clouds don't appear

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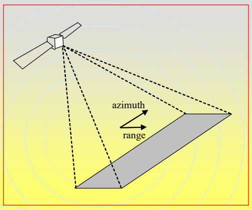
Real aperture radar imaging (RAR)



- Single transmitter with swept beam
- Resolution depends on beam width at object distance
- Fixed transmitter with dish
  - $1.22\lambda/d$ gives for a 3 m diameter dish operating at 10 GHz a spread of 0.7° ≡ 122 m at 10 km
    - OK for rain radar
    - ~10 km at 800 km
- Sweep in 2D achieved by motion of satellite

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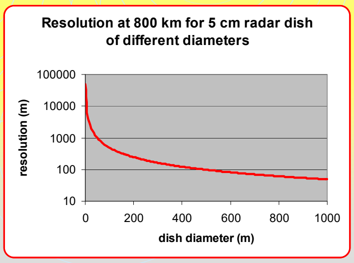
How big a dish for a resolution of 25 m from 800 km height?

- Take a wavelength of 5 cm
- 1 km diameter dish has resolution of 50 m
  - couldn't be launched!
  - 25 m resolution needs a dish 2 km in diameter



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- How is it done?

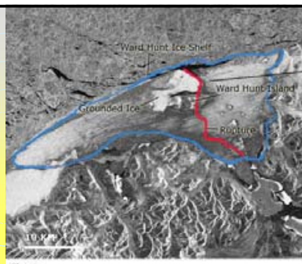

Fig. 1
In this Standard Beam Mode RADARSAT-1 image acquired September 27, 2003, the rupture (red) in the Ward Hunt Ice Shelf (area delineated by blue) can be easily located. A Standard Beam Mode image has a resolution of 25m. The scale bar represents 10km on the ground.

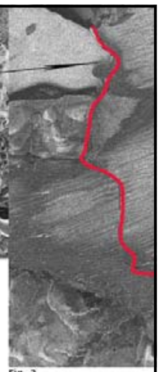

Fig. 2
By also imaging the Ward Hunt Ice Shelf with a RADARSAT-1 Fine Beam Mode image (resolution of 8m), the rupture in the ice shelf becomes even more apparent. This image was also acquired September 27, 2003.

25 m & 8 m resolution radar picture from over Antarctica

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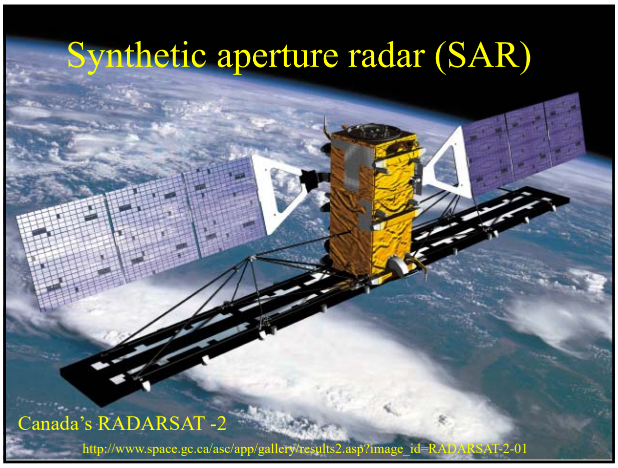

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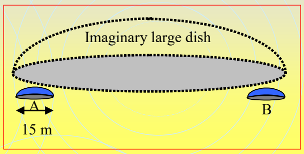
Combining together 2 observations

- Observation at point A is treated as part of reception from a large dish



- If observation from B is combined with that of A, can reconstruct a signal with the resolution appropriate to a large dish
- Method achieves the spatial resolution of a large dish but not the signal gathering power
  - complication that signal at B is recorded later
  - satellite moves at ~7.4 km s^{-1}

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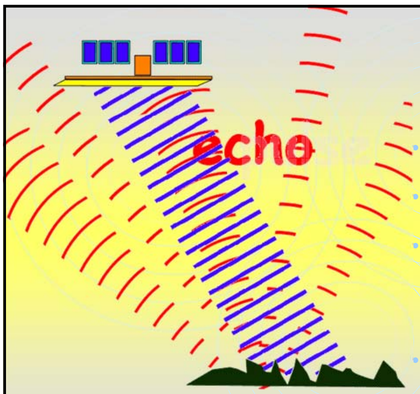
Sending & receiving



- Stream of pulses sent (blue in diag.)
- Aerial is a *phased array*
- Direction can be changed by altering signal phase at aerial elements
- Echo (red in diag.) continuously recorded

http://www.space.gc.ca/asc/img/trans_sar_diagram1.gif

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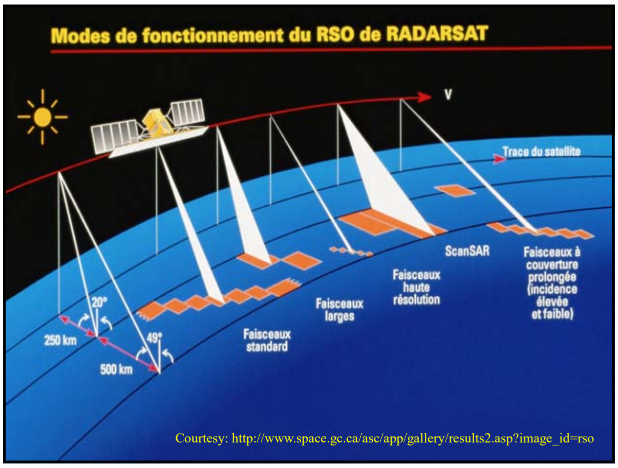

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Information in the image

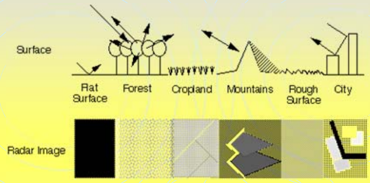

Fig courtesy: http://southport.jpl.nasa.gov/desc/imagingradarv3.html

- Echo signal depends on surface texture on scale of wavelength (5.66 cm for RADARSAT)
- Echo depends on dielectric properties of surface (microwave equivalent of refractive index)
  - ice and water are easily distinguished

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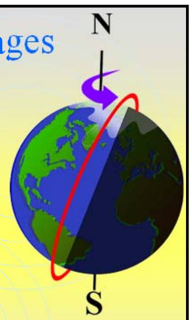
Features of radar images



- RADARSAT is in sun-synchronous, dawn/dusk polar orbit
- Constant wavelength, constant angle of illumination means that reflection signatures of surfaces are constant
  - unlike looking at sunlight surfaces
- Illumination is *coherent*, resulting in speckle like a laser
- Additional information can be obtained using polarisation as a variable
  - RADARSAT uses HH configuration, i.e. **sending** and **receiving** horizontal polarisation
  - single frequency/polarisation image is monochromatic

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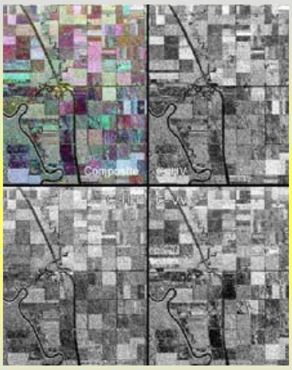
Polarisation gives extra information

- Polarisation measures the direction of the electric field of the radiation
- 3 C-band pictures
  - **HV** – Horizontal sent Vertical received
  - **HH** and **VV**
- False colour composite shows range of crops



http://www.space.gc.ca/asc/img/multipol1_b.jpg

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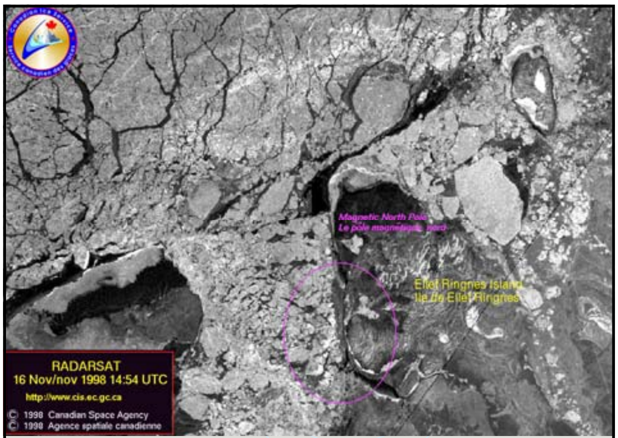

Courtesy: http:www.cis.ec.gc.ca/picmonth/rha9811161454.jpg

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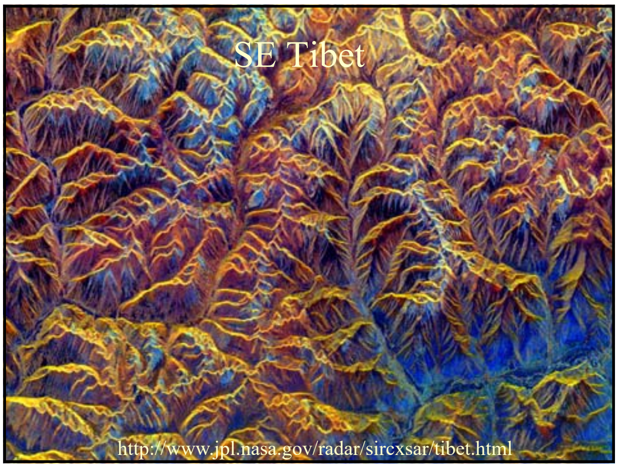

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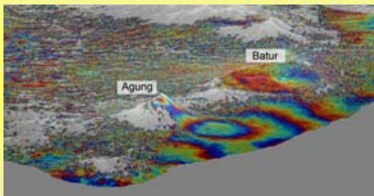
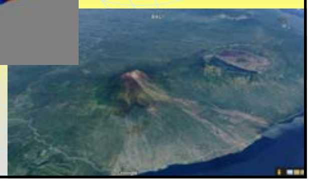
[InSAR]

- Interferometric Synthetic Aperture Radar
  - showing ground deformations



(Coloured) ground deformations from InSAR due to magma flow prior to eruption of Mt Agung in Bali. Courtesy: https://www.esa.int/spaceinimages/Images/2019/02/Volcanic_uplift



Aerial picture of Mts Agung & Batur, courtesy Google maps

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Communications

- A vital part of remote sensing
- The satellite communications business is the lucrative side of space technology
  - technological side is well developed
- Introduction to some concepts and jargon

http://earthobservatory.nasa.gov/Library/NOAA-M/Images/NOAA-M.jpg

uplink

downlink

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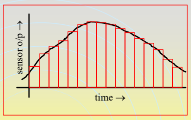
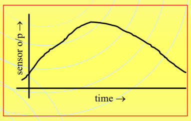
The digital age



- Many sensors return an **analog signal**
  - the signal varies in proportion to what is being measured



- Digitally, the signal is measured at equal time intervals
- The signal is measured in discrete steps
  - each step is numbered in binary
  - e.g. 256 steps can be represented as an 8-bit binary number such as 00011011 (step 1 + 2 + 8 + 16 = 27)

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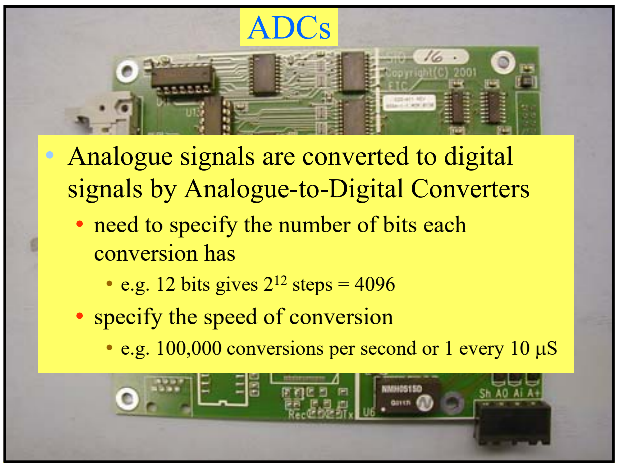

ADCs

- Analogue signals are converted to digital signals by Analogue-to-Digital Converters
  - need to specify the number of bits each conversion has
    - e.g. 12 bits gives 2^{12} steps = 4096
  - specify the speed of conversion
    - e.g. 100,000 conversions per second or 1 every 10 µS

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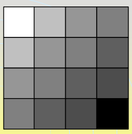
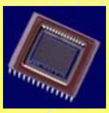
Pictures are divided into pixels

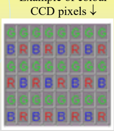


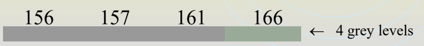
- Grey levels may be represented by an 8-bit binary number (1 byte)
  - e.g. range 00000000 for black to 11111111 for white
  - e.g. pictures could be transmitted by rows



- Why is binary better than analogue?
  - **NOISE IMMUNITY**

Example of colour CCD pixels ↓





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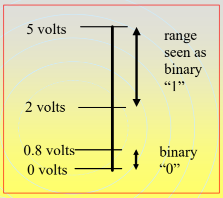
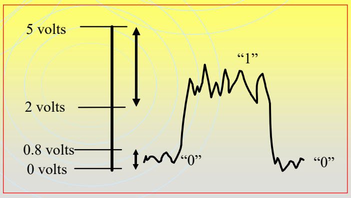
TTL signals



- TTL is the logic used in many digital circuits
  - the operating voltage may be as low as 2.4 volts
- Modest random fluctuations in voltage make no difference to the "1" and "0" signals
  - this is **noise immunity**



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What happens if the noise is too big?

- The signals are corrupted in transit
  - the message arrives witd wronk churacters, a wrong reading or the wrong level in a picture
  - e.g. 0001 sent arrives 0011 if there is one error
    - 0001 could arrive as 1011 with 2 errors
- How can you detect the presence of an error?
  - you need to transmit extra information
  - one error can be detected by a **parity check**

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Parity

00101011 – even parity

00001011 – odd parity

- Parity is the number of "1"s present
  - even parity is an even number of "1"s
  - odd parity is an odd number of "1"s
- Add a parity bit to a word or packet, either first or last
- Two operational schemes
  - common scheme: whole word, including the parity bit, has the parity expected
- E.g. sending 0001with even parity, send 00011
  - if 00111 arrives, then a parity check spots the error
- Parity checks can't determine what the error is
  - they can initiate request for a re-send

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Long distance signals are noisy

- E.g. the Sojourner Mars rover broadcast with only a few watts of power
  - comparable with an ordinary torch bulb
  - signal is very weak on arrival
  - can't ask for a re-send
  - need error code that allows errors to be detected **and** corrected

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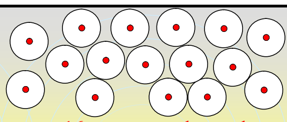
What is the problem?



16 separate code words

- With compact coding using minimum of bits, an error will produce an alternative valid code
  - need *distance* between valid codes
- **Distance** between codes is the number of different symbols they have
- e.g. 00000111 and 00101011 have distance 3 between them
- Richard Hamming showed that if the distance between all code words in a message is *n* then you can correct up to (*n* – 1)/2 errors per word
  - minimum Hamming distance to correct for 1 error is 3

Richard W. Hamming 1915 - 1998

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How can error correction work?

- In the 7-bit code words on right, there is a Hamming distance of at least 3 between any 2 words
  - first 4 bits are normal binary codes
  - send 7 bits, not 4
    - e.g. 0011010 for 3
    - if 0111010 arrives, nearest acceptable code word is 0011010, distance only 1 away hence single bit error is corrected and interpretation is 3
- All codes a distance 1 away from a given number refer to the same number

0	0000000
1	0001101
2	0010111
3	0011010
4	0100011
5	0101110
6	0110100
7	0111001
8	1000110
9	1001011
10	1010001
11	1011100
12	1100101
13	1101000
14	1110010
15	1111111

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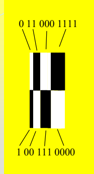
Examples for you to investigate

0-314-02779-3 ← ISBN

← UPC

- There are error correction codes in
  - ISBN numbers – 9 digits + checksum to base 11
  - UPC numbers – 13 digits + checksum to base 10
  - airline tickets – checksum to base 7
  - barcodes –each digit represented by 7 bits
  - banknote numbers
  - coding of tracks on CDs and DVDs



Barcodes: width of a section tells the number of bits

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Some error correction strategies

- Forward error correction (FEC)
  - inclusion of extra information allowing transmission errors to be corrected
    - last slide showed example
    - good for noisy and long-distance channels
- Automatic repeat request (ARR)
  - message divided into packets whose integrity is checked
  - integrity failure triggers re-send request
- Stop and wait (SW)
  - sender requires acknowledgement of each packet

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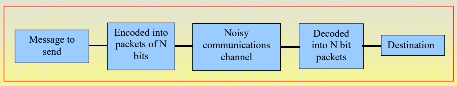
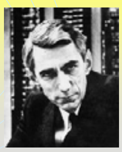
The communications limit



- There is a fundamental limit on the rate of transmission of error-free information
  - this is a law of nature
  - applies to every form of communication
- Discovered by Claude Shannon and published in 1948
  - Shannon's (noisy channel) law



Claude E Shannon 1916 - 2001

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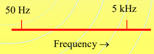
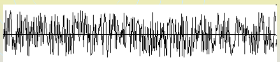
What determines communication rates?

- Bandwidth, B in Hertz
  - the range of frequencies available for the communication
    - e.g. telephone line might be ~5 kHz
    - the communications channel allows a wide range of signal strengths (an analogue channel)



- Signal to noise ratio, S/N
  - measured as a ratio of the signal power to the noise power



Noise masking a signal

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Shannon's law

- The capacity of the communications channel, C, is the maximum number of bits per second
- $C = B \times \log_2(1 + S/N)$ $\log_2 = 3.322 \times \log_{10}$
  - this is a natural limit
    - with suitable error correcting means you can in principle transmit error-free messages up to the capacity limit C
    - errors may accumulate without limit above C
  - real systems generally do a lot worse than C
- e.g. B = 5 kHz; S/N = 100; $C = 5000\log_2(101) = 33.3$ kbits s^{-1}
  - if S/N = 1, $C = 5000\log_2 2 = 5$ kbits s^{-1}

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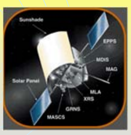
Pushing for the limit

- The limit determines
  - the usable range of mobile phones from transmitters
  - the power needed at mobile phone masts
  - the range of wireless networks **hotspot**
  - the communications power needed by satellites and space probes
  - much more!



The MESSENGER spacecraft that uses new generation error coding communication

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Approaching the limit

- 21st century engineers are finally learning how to get the maximum error free transmissions
  - this has enormous practical impact
- LDPC – **L**ow **D**ensity **P**arity **C**heck coding
  - large code words (e.g. > 1000 bits)
  - a large no. of parity bits for selected sums of bits within the word are included in a code word
  - easy to code
  - needs multi-processor electronics to decode
  - gets close to the Shannon capacity limit

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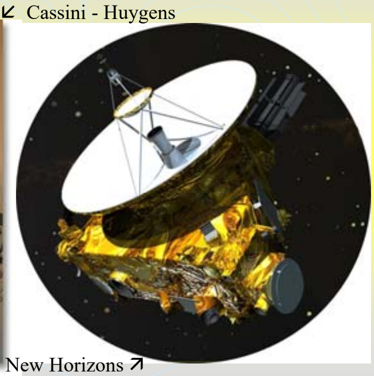
Communications are important

↙ Cassini - Huygens



New Horizons ↗

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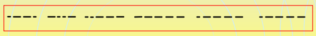
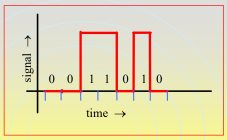
Transmitting the signal





- Early morse telegraphy just switched off and on the current with the morse key
- Nowadays the signal is impressed on a **carrier wave**
- This process is called **modulation**
  - extracting the signal is called **demodulation**
  - a **modem** is a **mod**ulator/**dem**odulator

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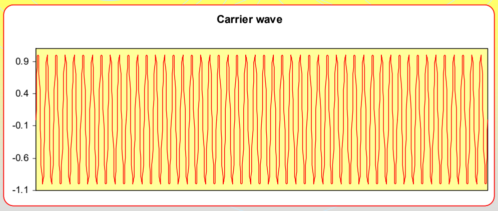
- Signals are sent on a **carrier wave** consisting of a sinusoidal wave of definite frequency
- The sketch shows 50 periods of a carrier wave
- The carrier contains no information



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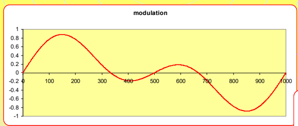
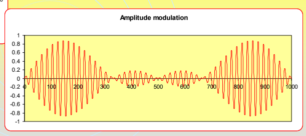
Amplitude modulation

- Amplitude modulation (AM) involves changing the amplitude of the carrier in proportional to the information signal you want to send



← Signal to be sent



Amplitude modulated result →

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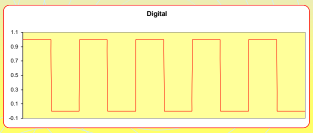
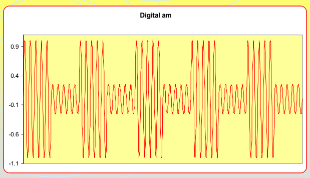
Digital amplitude modulation

- The digital signal consists of “1”s and “0”s
  - example here is 1010101010
- A digital AM version is shown below





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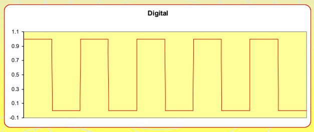
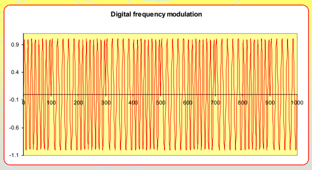
Digital frequency modulation

- The frequency is changed according to the signal size
- A digit signal has just 2 values
  - 2 frequencies present
    - effect is exaggerated in the sketch
  - traditionally known as **FSK** (frequency shift keying)





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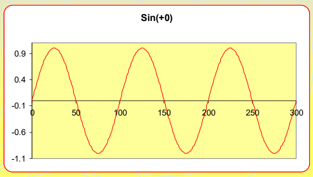
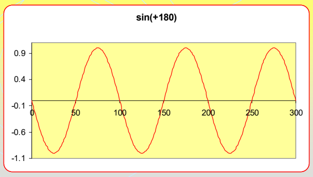
Phase modulation

- Most digital communications uses **phase modulation**
  - top signal can be used for “0”
  - bottom signal for “1”
  - neither frequency nor amplitude change
- There are phase jumps every time digital input changes





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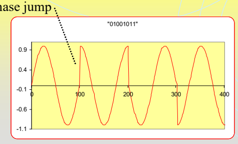
QPSK

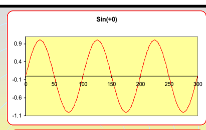
- QPSK – **quadrature phase shift keying**
- 2 bits sent at a time
  - known as a **dibit**
- Each pair of bits is represented by a signal of different phase

Phase jump



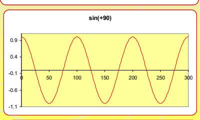
dibit 01 →

Phase 0º



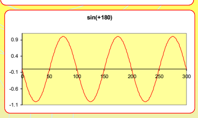
dibit 00 →

Phase 90º



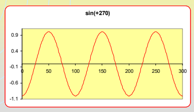
dibit 10 →

Phase 180º



dibit 11 →

Phase 270º



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Demodulation

- Demodulation means extracting the superimposed information from the carrier
- **Modem** (modulator/demodulator)
  - a modem modulates the uplink and demodulates the downlink
  - each type of modulation has its corresponding technique of demodulation
  - Demodulating QPSK is not difficult

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Demodulating QPSK

- Multiply the incoming signal at frequency ω ($\sin(\omega t + \phi)$) by a signal of the same frequency
- **For the mathematical**:
  - $\sin(\omega t + \phi) \times \sin(\omega t) = \frac{1}{2}\cos\phi - \frac{1}{2}\cos(2\omega t + \phi)$
- The result is a signal that depends on $\cos\phi$ plus a signal at twice the frequency (which is discarded)
  - doing the same but multiplying by $\cos(\omega t)$ gives $\sin\phi$
- Once you know both $\cos\phi$ and $\sin\phi$ you can find ϕ
- When you know ϕ, you know the dibit 01, 00, 10, 11

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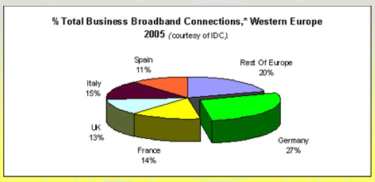
Aside on Broadband



- ADSL – asymmetric digital subscriber line
  - typically up to 2 Mbit s^{-1} across copper wire
  - downlink is faster than uplink
    - 512 kb s^{-1}; 256 kb s^{-1} upstream
    - built-in forward error correction

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A final word or two on graphics

- On a 'full-colour' computer screen, each pixel is determined by the intensity of a red, green and blue component
  - each component is specified by 1 byte (containing 8 bits)
    - total 24 bits per pixel
- Example in next slides

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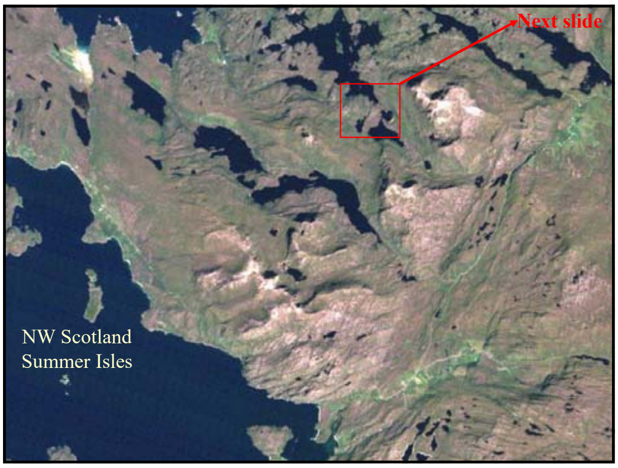

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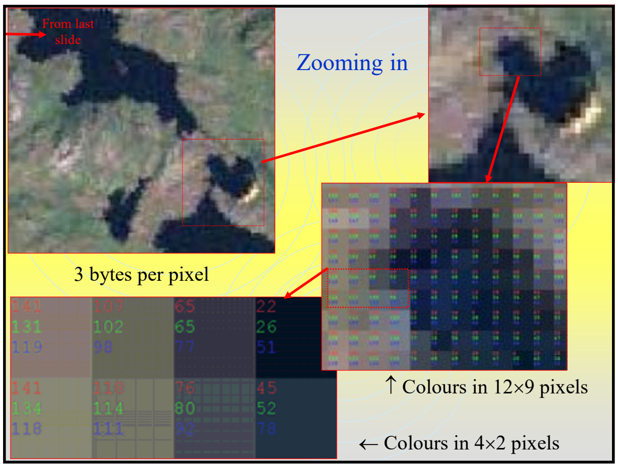

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Jpeg compression

- JPEG (**J**oint **P**hotographic **E**xperts **G**roup)
- Reduces file size from bit-map proportions
  - intrinsically lossy but ………
  - factor 10 compression with hardly noticeable loss
- Optimised to human visual system
  - works on 24 bit pixels
  - preserves intensity, sacrifices some colour
  - not so good on sharp edges
    - e.g. small text
  - user selectable compression factor, trading file size and lossiness

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Gif compression

- Gif – **G**raphics **I**nterchange **F**ormat
  - compression technique and standard format
- No loss of detail
- Compacts repeated strings of data
- Uses 1 byte (8 bits) per pixel
  - ideal for black, grey and white images
  - can only handle 256 colour palette
  - does preserve sharp edges
  - good for diagrammatic material
  - can include transparent background
  - can be made animated

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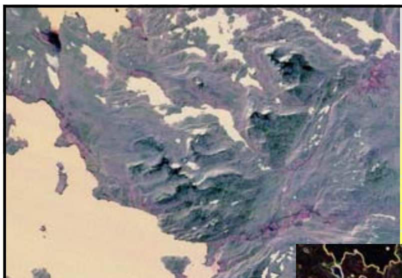
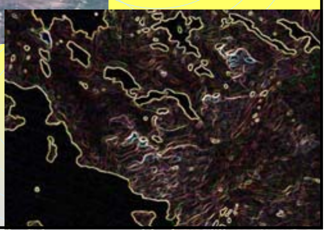


Digital Signal Processing

←Simple inverse

↓ Edge highlighting



Original ↓

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Summary

- Course has taken a wide view of space science with a particular eye on remote sensing as one application
  - many will meet detailed applications of remote sensing in 3rd and 4th year courses
- Many of the subjects you’ve met with are not dealt with in any other BSc courses at Aberdeen yet are very relevant to 21st century life
  - I originally planned to repeat some *light science* from that course relevant to false colour maps but have omitted it
- Good luck with revision and future courses!

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