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Earth observation and navigation

Space technology I

Vendela Paxal

Overview

- Applications
- Fundamental definitions and limitations
- Observation techniques
- Navigation - GPS

Applications earth observation

- Habitation
- Agriculture & fishing
- Transport
- Oil spill and other environmental damages
- Earth quakes & volcanos
- Tsunamis
- Climate changes & ozon layer
- Floods
- Forest fires
- Weather
- Wave hight and direction
- Temprature
- Military installations and movement
- etc.......

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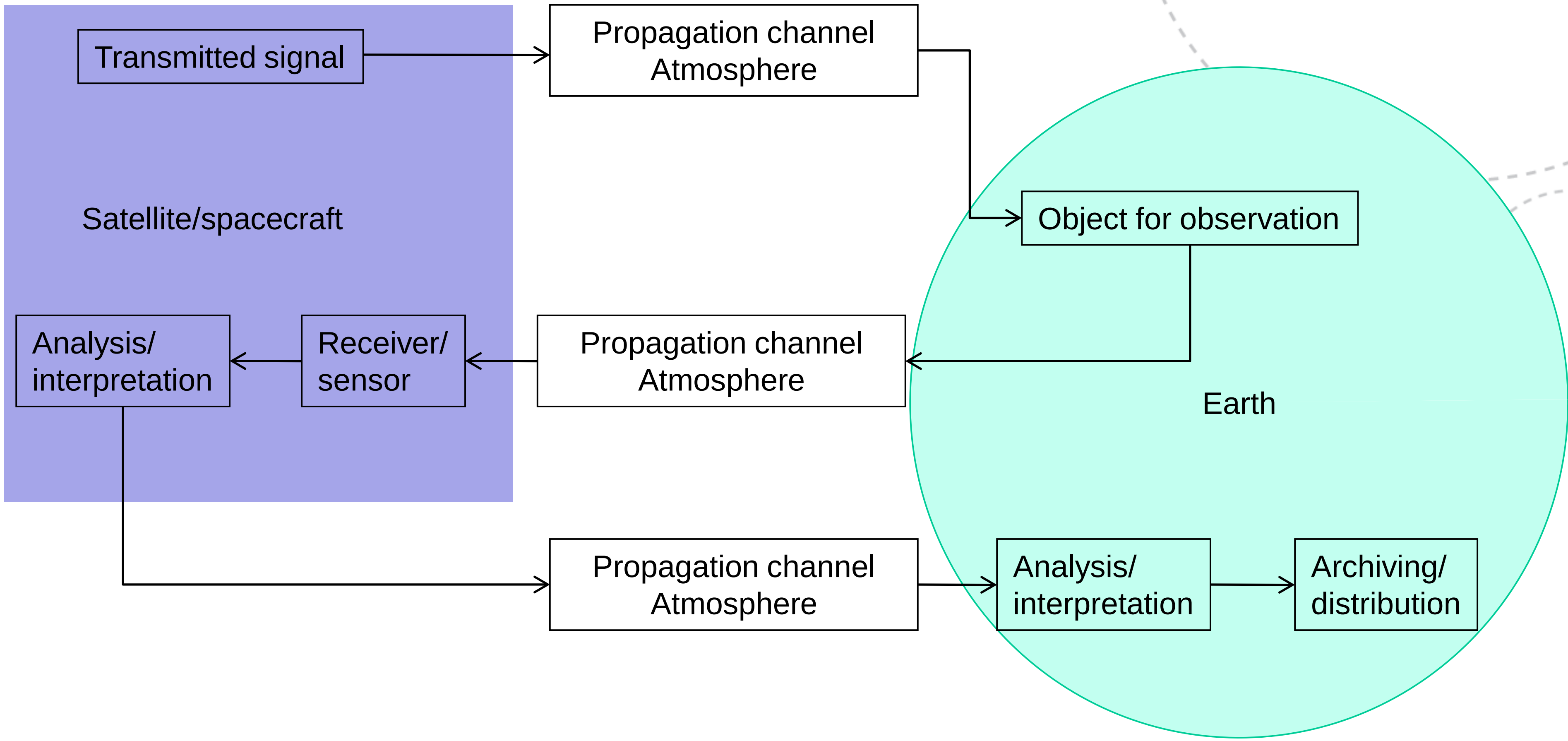
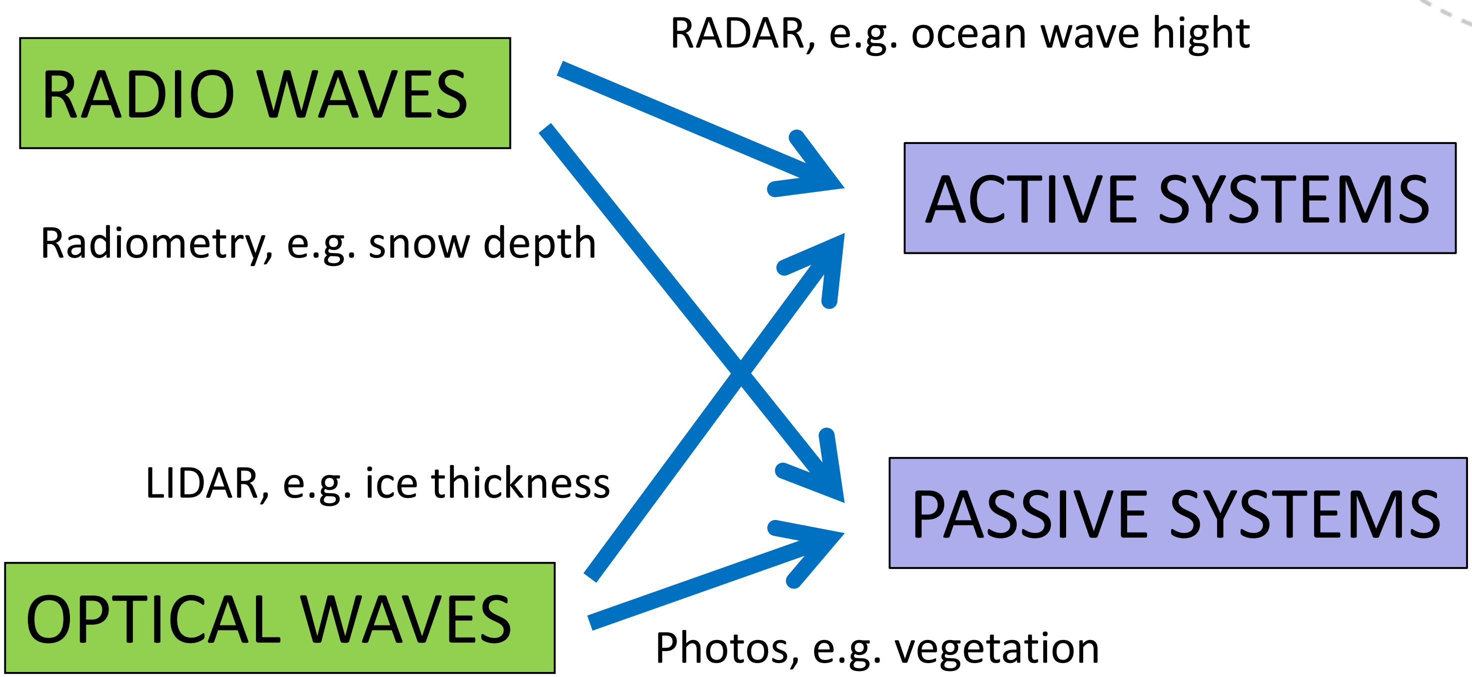
Genaral observation system



Active and passive systems



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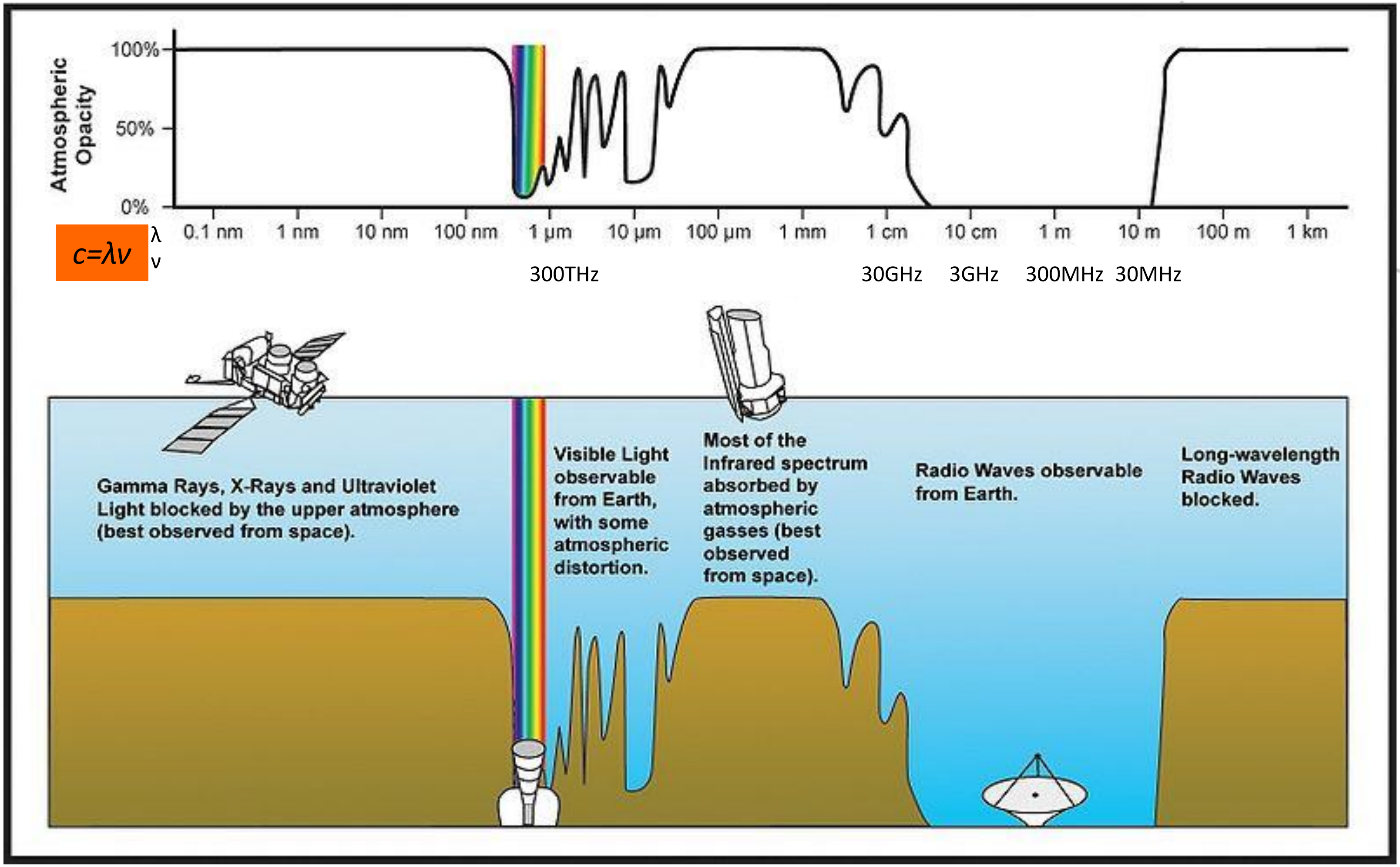
Atmospheric windows



Free space loss: $L_0=(4\pi d/\lambda)^2=(4\pi d\nu/c)^2$

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Resolution

- Aperture
- Resolution
- Techniques to improve resolution

Aperture

The size of the aperture, and the wavelength of radiation, determine the smallest object we can see – the resolution

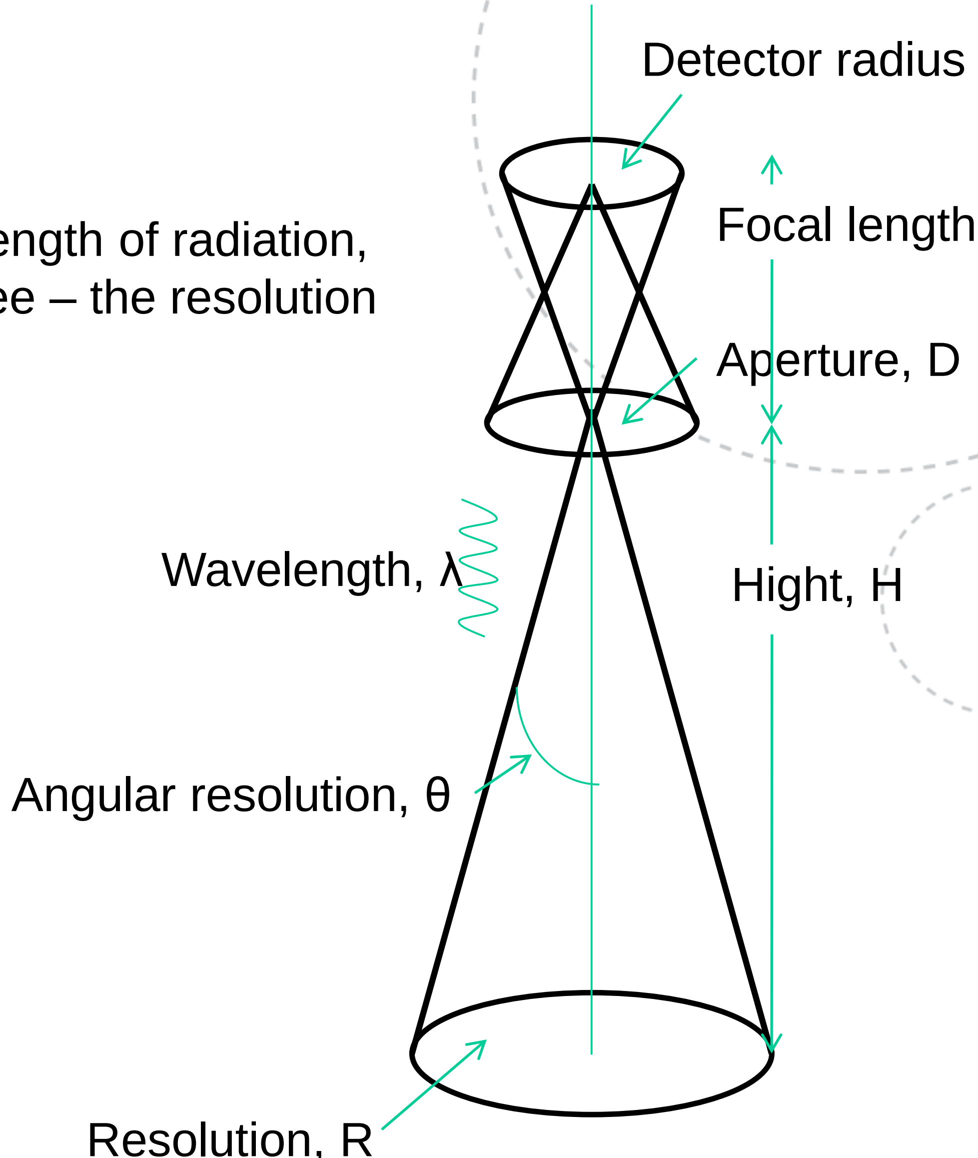
Defenitions:

Angular resolution:

$$\theta = \frac{1.22\ \lambda}{D}$$

Resolution:

$$R = \frac{2.44\ \lambda H}{D}$$



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Examples

Radar:
$\lambda = 0.03m$
$\nu = 10GHz$
$D = 3m$
$H = 1000km$

$$\text{Resolution: } R = \frac{2.44\,\lambda H}{D} = \frac{2.44\times 0.03\times 10^6}{3} = 24400m$$

Optical:
$\lambda = 0.5\mu m$
$\nu = 6\times 10^{14}Hz$
$D = 10cm$
$H = 1000km$

$$\text{Resolution: } R = \frac{2.44\,\lambda H}{D} = \frac{2.44\times 0.5\times 10^{-6}\times 10^6}{0.1} = 12m$$

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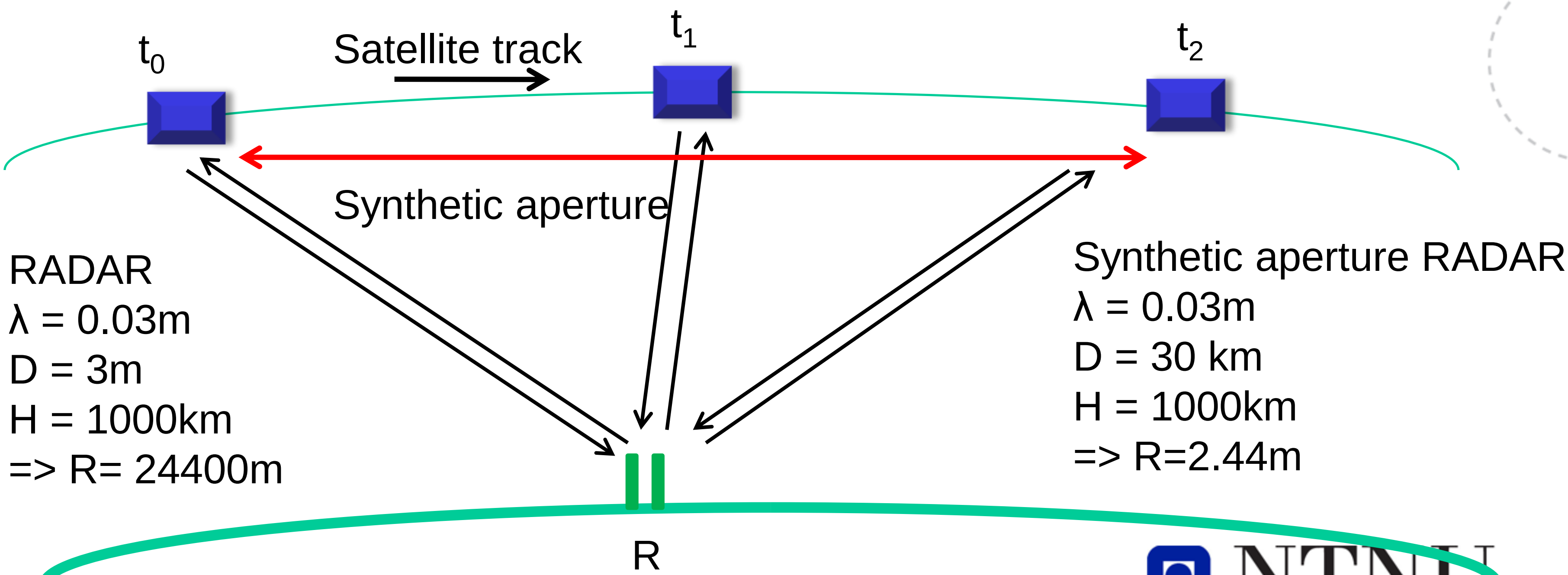
Resolution problem

- The resolution is determined by the wavelength
- Light has a short wavelength, and hence a good resolution, but is not practical due to clouds and darkness.
- Radio waves have better penetration in the athmosphere, but give poor resolution.
- This can be remedied by using synthetic aperture or pulse compression.

Synthetic aperture (spotlight)

The transmitted pulses and the reflections are processed wrt amplitude, phase and position. The RADAR aperture will then be equivalent to an aperture equal to the distance of the satellite track. This gives a large synthetic aperture.



Pulse signal detection

The simplest signal, *s(t),* a pulse radar can transmit is a sinusoidal pulse of amplitude *A* and carrier frequency f_0, truncated by a rectangular function $\Pi(t)$ of width *T*.

$$s(t) = \Pi(t) \times A e^{2i\pi f_0 t}$$

The cross correlation between the transmitted signal and the reflected signal *r(t)* gives a time shifted sinusoidal pulse, truncated by a triangular function $\Lambda(t)$ of width 2*T*.

$$\langle s,r\rangle(t) = \xi \times A^2\, \Lambda((t-t_r))\, e^{2i\pi f_0 (t-t_r)} + n(t)$$

ξ is an attenuation factor,

n(t) is noise, assumed additive white gaussian (AWGN).

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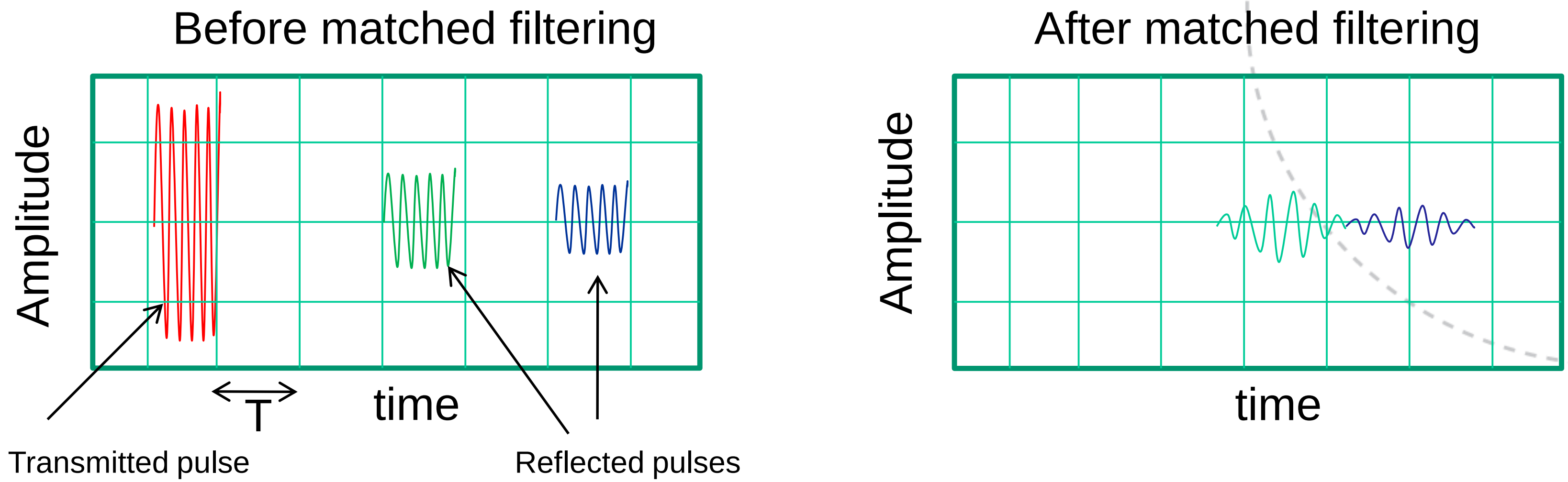


In order to be able to separate the pulses at reception, the distance between the reflected pulses must be superior to T.
The range resolution is *R=c·T/2.* To improve the resolution T must be reduced.
c is the speed of light.

But, the signal to noise ratio at reception: SNR= $\xi^2 A^2 T/\sigma$, where σ is the standard deviation of the noise.

Hence, to maintain detection of the signal, T can not be reduced.

R=cT/2, see figures 2 & 3 at http://www.radartutorial.eu/01.basics/rb18.en.html

Chirp signals

Problem: how can we obtain a large enough pulse with acceptable resolution?

- The transmitted signal must have a long enough pulse in order to maintain a correct energy budget
- The signal width after matched filtering must reduce the signal pulse time; pulse compression.

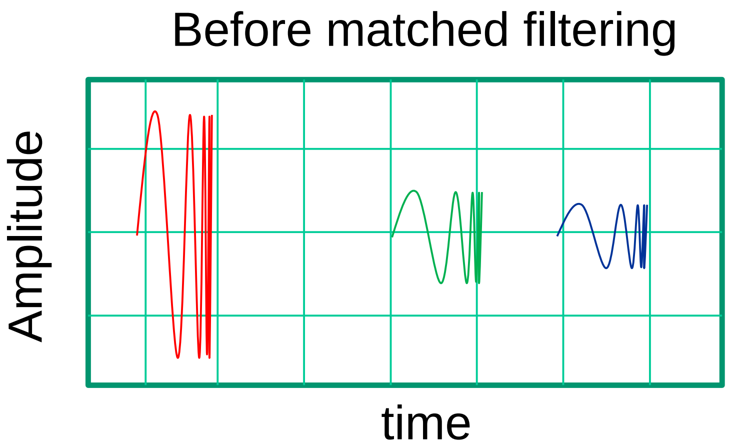
The pulse being of finite length, the amplitude is a rectangle function, $\Pi(t)$. If the transmitted signal has a duration T, begins at t = -T/2 and linearly sweeps the frequency band Δf centered on carrier f_0:

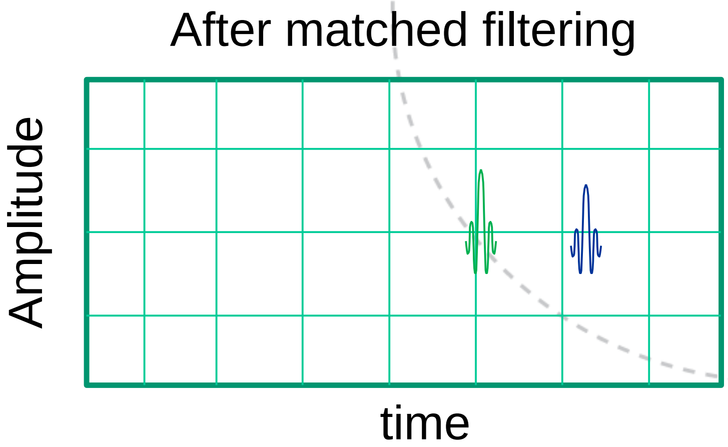
$$s(t) = \Pi(t) \times A e^{2i\pi(f_0 + \Delta f t/2T)t}$$

This is called a linear chirp; a signal where the frequency varies linearly with time.

After matched filtering, the signal becomes:

$$<s,r>(t) = \xi \times A^2\, \mathrm{T} \times \Lambda((t-t_r)) \times sinc(\pi \Delta f t \Lambda((t-t_r))) \times e^{2i\pi f_0 (t-t_r)} + n(t)$$





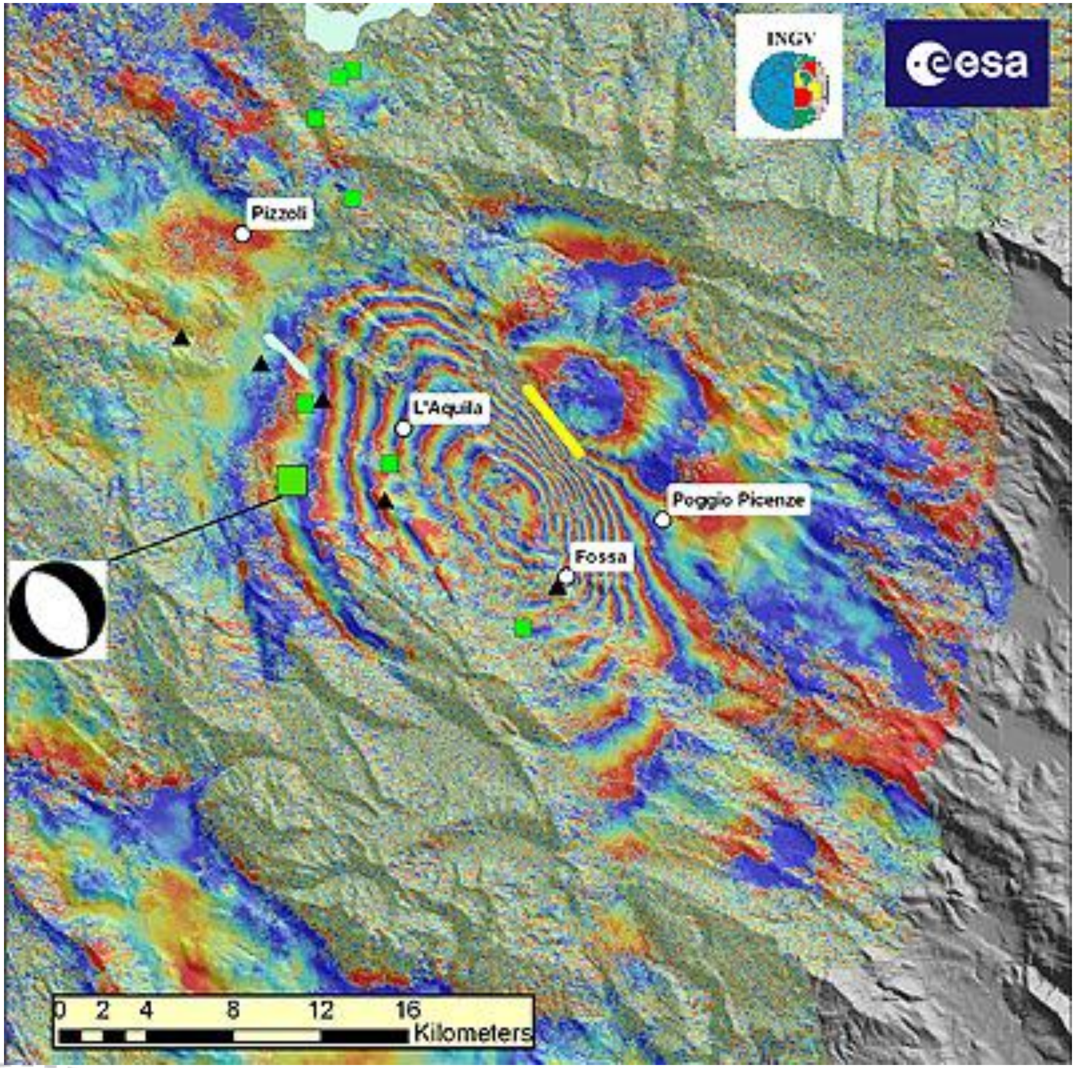
The -3dB width of the main lobe is $T' = 1/\Delta f$. The side lobes can be filtered out. The resolution range is thus $R = c/(2\Delta f)$.

The pulse compression ratio is $C = T/T' = T\,\Delta f$. The goal is to have $C > 1$, it is usually between 20 and 30.

Interferometry

- Technique
- Applications and examples

L’Aquila eartquake 2009



Interferogram generated by Italy’s Istituto per il Rilevamento Elettromagnetico dell’ Ambiente (IREA-CNR) in Naples, Italy

Envisat (ESA) interferogram over the L’Aquila area in central Italy showing the deformation pattern caused by the seismic events in early April 2009.

Measurement acquisition on 12 April 2009 combined with a pre-seismic acquisition on 1 February 2009

Each color cycle, is equivalent to an Earth surface displacement of 2.8 cm along the satellite direction.

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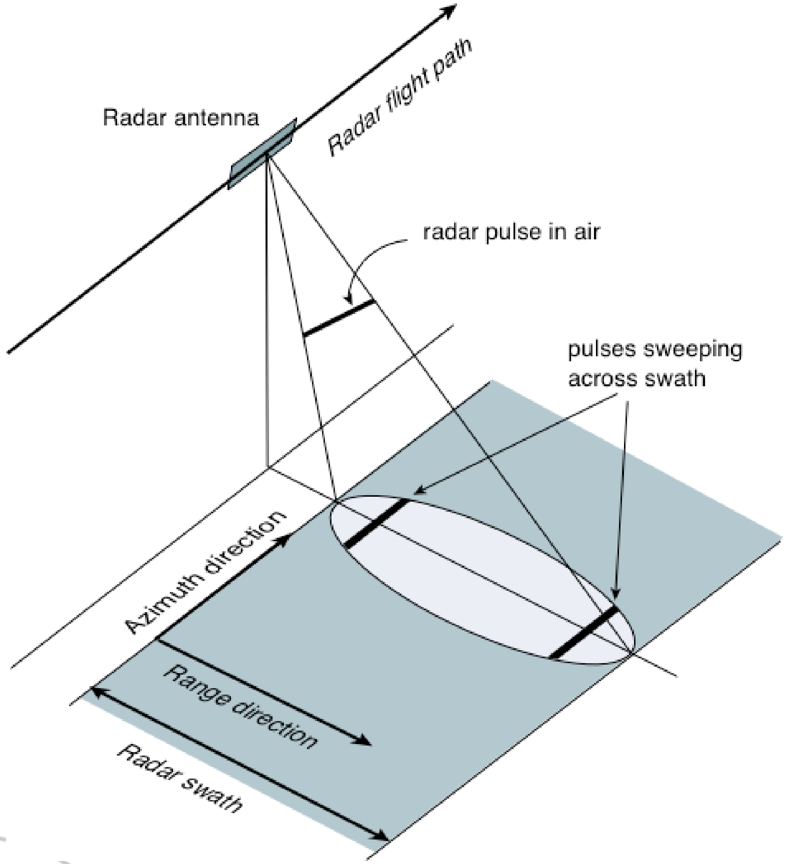
From http://envisat.esa.int/ , http://www.esa.int/esaCP/SEM4PJ9NJTF_index_1.html#subhead1

Radar Interferometry measurements

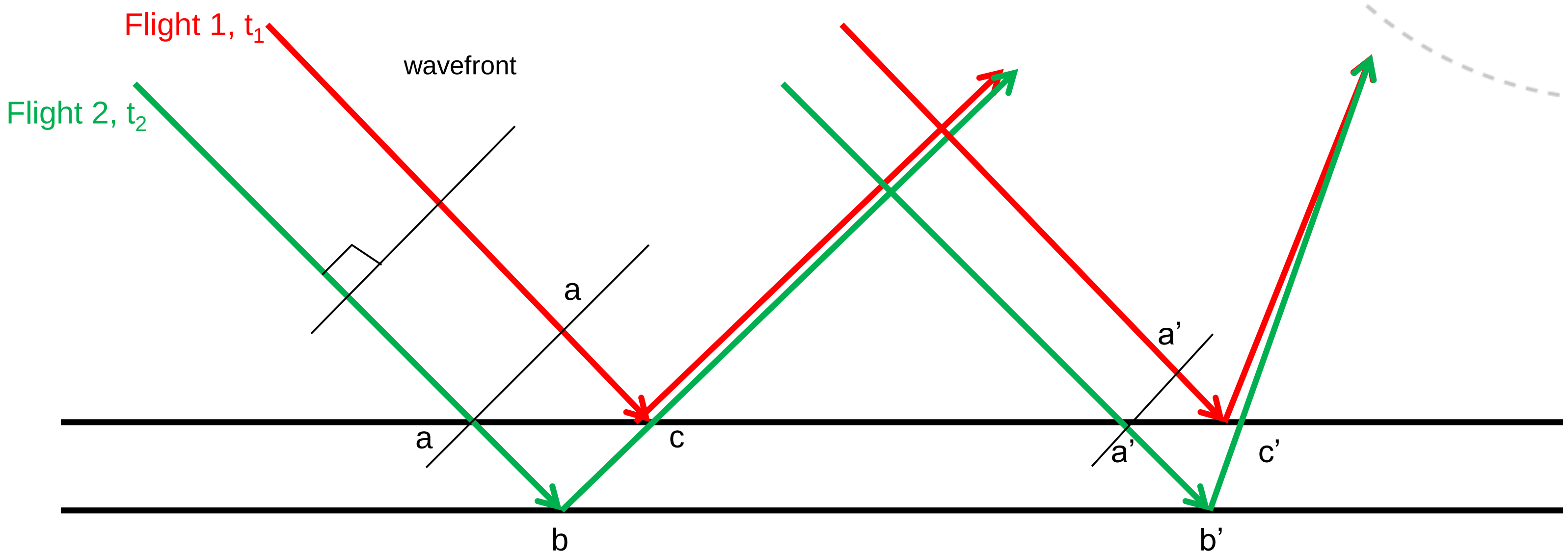


Pulses are transmitted from the radar platform as it moves along its flight path.
Some of the energy from the ground is scattered (not mirrored) back to the radar instrument

http://www.grss-ieee.org/files/Radar_Interferometry_Part1.pdf

Interferometri, and positioning

Comparison of reflected images at two distinct instants gives information about changes.



Path:(a-c)

Path:(a-b-c)

If (a-b-c)-(a-c) = nλ, then we have constructive interference

If (a-b-c)-(a-c) = (n+1/2)λ, then we have destructive interference

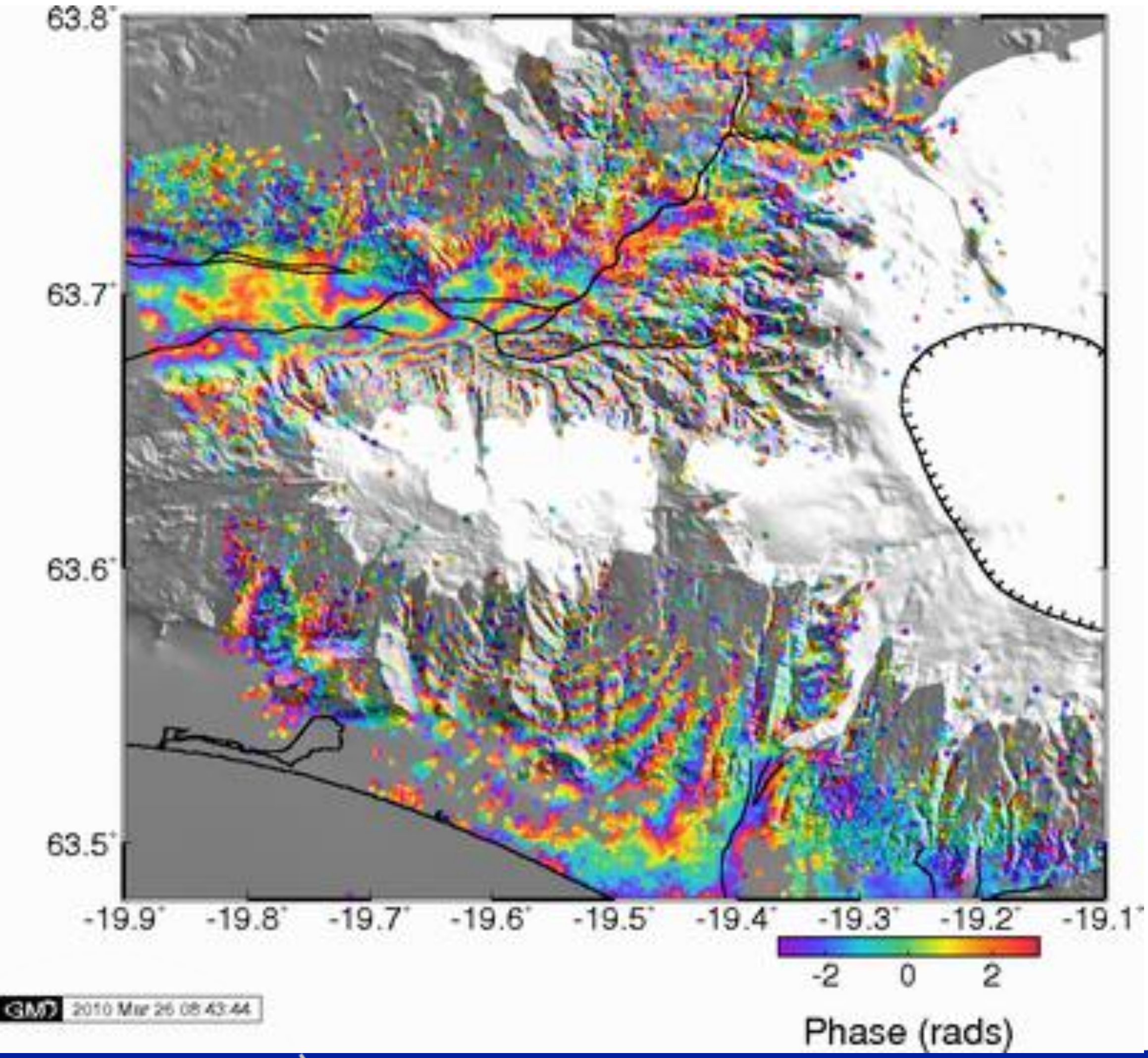
NB! You need to know the exact position of the satellite.

Example: Etna observation
from 1992-2006 based on ESA's ERS-1, ERS-2 and Envisat satellites.

http://www.esa.int/esaCP/SEMQGHKTYRF_index_1.html

Etna is one of Europe's most active volcanoes, and has had eruptions (principal and flank) almost every year over a period of 15 years, especially active after year 2000.

Eyjafjallajøkull
preceding the March 20th 2010 eruption



"First interferometric analysis of synthetic aperture radar images acquired by satellites reveal extensive deformation associated with a magmatic intrusion under Eyjafjallajökull preceding the eruption. The deformation signal appear as colour fringes, where each fringe represents a change in range from ground to satellite of 1.5 cm. Extensive deformation is observed both north and south of Eyjafjallajökull.

The image shows a large change in range from ground to satellite between September 1999 and March 20, 2010, just prior to the eruption that began around 22:30 GMT. These are the first in a series of interferograms anticipated to be formed showing the course of the eruption.

The interferograms are formed by analysing images from the German TerraSAR-X satellite. The research is a collaborative project between the Nordic Volcanological Center at the Institute of Earth Sciences, University of Iceland, the Technical University of Delft, Netherlands, and the University of Wisconsin-Madison, USA. The initial interferograms have been formed by Andy Hooper at Delft."

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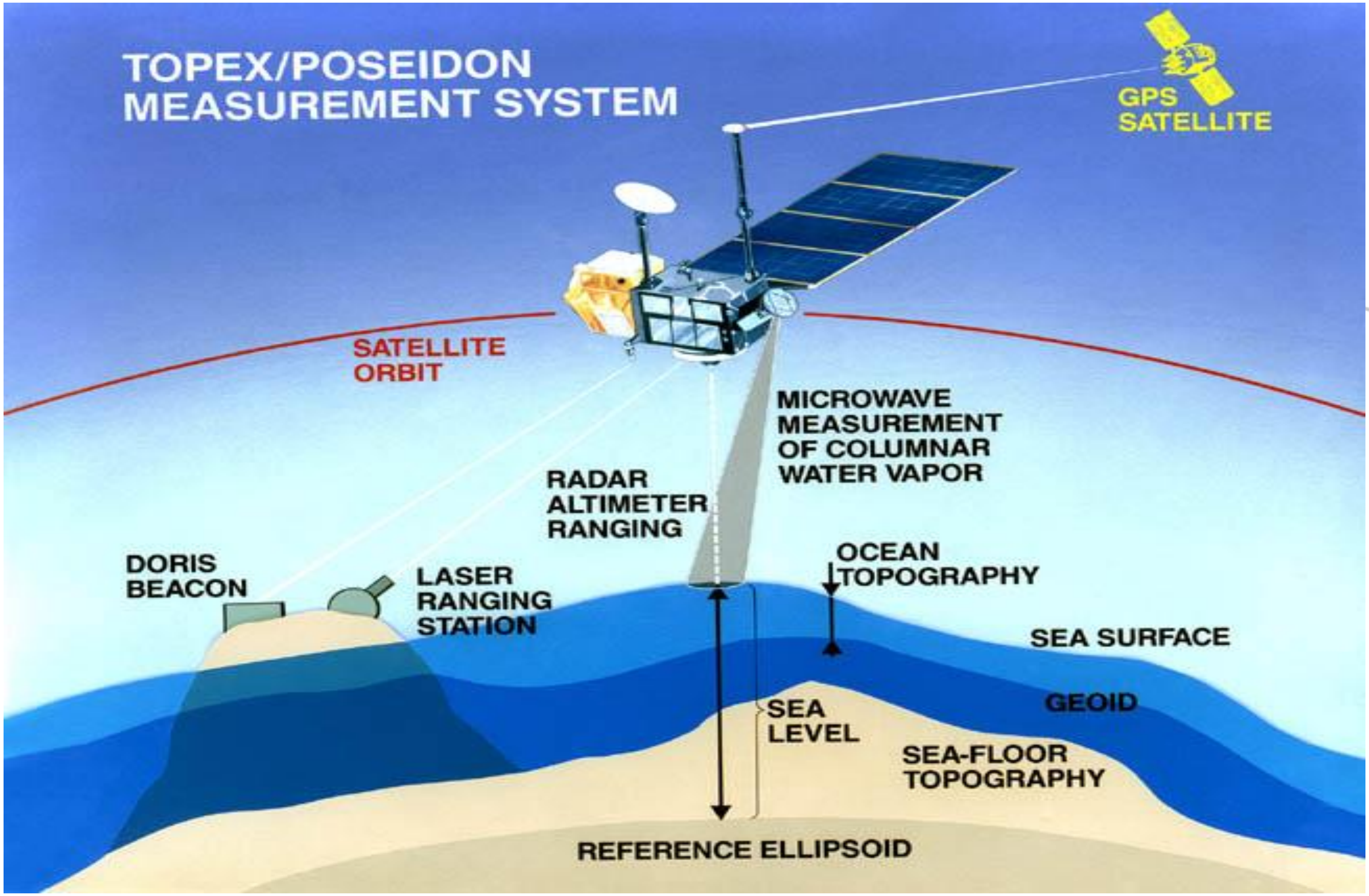
http://yusuke-s.tumblr.com/post/484148523/eruption-in-eyjafjallajokull-a-view-from-space-on

Radar altimeter and positioning

- Technique
- Application with example

Hight mesurements with RADAR



Oceanic observation – Topex/Poseidon

- Launched in 1992
- Joint satellite mission between NASA and CNES
- Mission: to map ocean surface topography
- radar altimeter using C-band (5.3GHz) and Ku-band (13.6 GHz)
- Radiometer at 18, 21 and 37GHz to correct for atmospheric wet path delay
- orbit 1330 kilometers above Earth
- measurements of the surface height of 95 percent of the ice-free ocean
- an accuracy of 3-4 centimeters
- Goal: determine patters of ocean circulation in order to improve climate predictions
- Turned off in 2006 due to problems
- Jason satellite series (1-2-3…) take over

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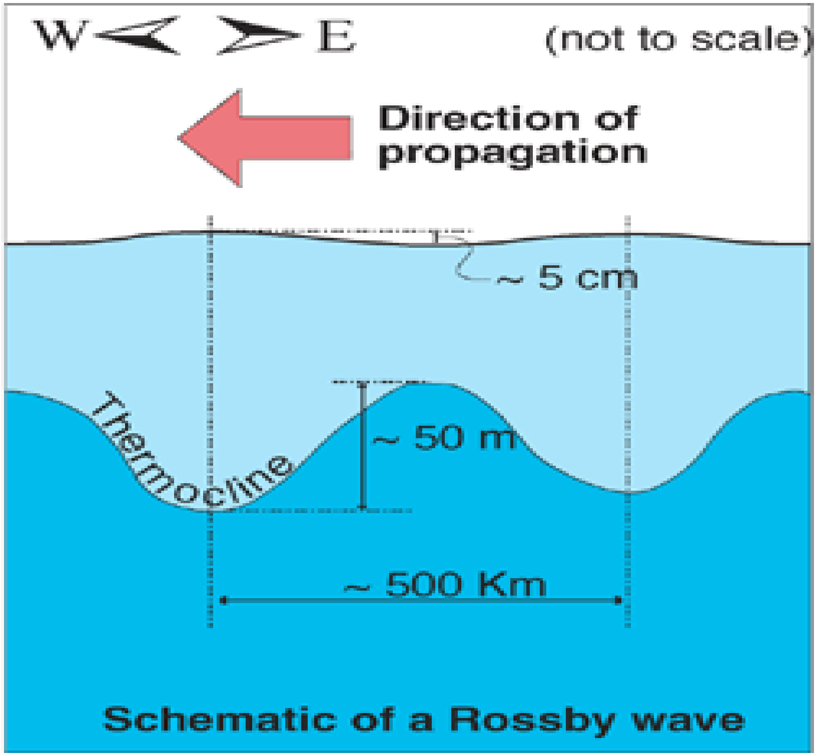
http://topex-www.jpl.nasa.gov/

The Topex/Poseidon mission

- Measured sea level with an unprecedented accuracy
- Mapped global tides for the first time
- Monitored effects of currents on global climate change and produced the first global views of seasonal changes of currents
- Monitored large-scale ocean features like Rossby and Kelvin waves and studied such phenomena as El Niño, La Niña, and the Pacific Decadal Oscillation
- Mapped basin-wide current variations and provided global data to validate models of ocean circulation
- Mapped year-to-year changes in heat stored in the upper ocean
- Improved our knowledge of Earth's gravity field

Rossby: http://www.noc.soton.ac.uk/JRD/SAT/Rossby/Rossbyintro.html
Rossby&Kelvin: http://www.aviso.oceanobs.com/en/applications/ocean/large-scale-circulation/rossby-kelvin-waves/index.html
El Niño, La Niña: http://en.wikipedia.org/wiki/El_nino
Pacific decadal Oscillation: http://en.wikipedia.org/wiki/Pacific_decadal_oscillation

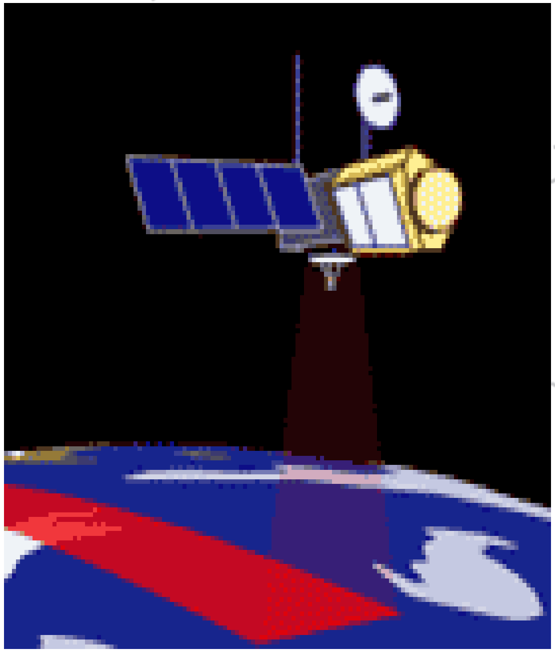
Example: Rossby waves



Planetary wave originating from the rotation of the earth. Long wavelength and slowly moving. They travel from east to west at speeds of ~km/day. It may take months or years for them to cross the pacific ocean (depending on the latitude).
Predicted in the 1930's, confirmed first with use of satellites. They play an important role in meteorology and climate variations.
A Rossby wave can deviate the Gulf stream.

Radar altimeter

- Two radar altimeters measured the distance from the satellite to the ocean surface:
  - the NASA TOPEX instrument beams microwaves at 13.6 and 5.3 GHz;
  - the CNES POSEIDON instrument, at 13.65 GHz.
- The principle is to transmit radar pulses in the direction of the sea. The pulses are reflected, and the reception time will give the distance, d=ct.
- Correction for atmospheric and instrumental effects is necessary, but when performed, the TOPEX/Poseidon distance measurements are accurate to 3-4 centimeters.



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http://topex-www.jpl.nasa.gov/technology/technology.html

Position determination Topex/Poseidon

Three independent tracking systems determined the position of the spacecraft:

1. The NASA laser retroreflector array (LRA) reflected laser beams from a network of 10 to 15 ground-based laser ranging stations under clear skies.

2. The CNES Doppler Orbitography and Radiopositioning Integrated by Satellite tracking system receiver (DORIS) provided all-weather, global tracking. This device uses microwave Doppler techniques to track the spacecraft. DORIS consists of an on-board receiver and a global network of 40 to 50 ground-based transmitting stations.

3. An on-board experimental Global Positioning System (GPS) demonstration receiver to precisely determine the satellite's position continuously by analyzing the signals received from the U.S Air Force's GPS constellation of Earth orbiting satellites.

TOPEX/Poseidon was the first mission to demonstrate that the Global Positioning System could be used to determine a spacecraft's exact location and track it in orbit. Knowing the satellite's precise position to within 2 centimeters in altitude was a key component in making accurate ocean height measurements possible.

Scientific use of data from Topex/Poseidon

- Climate research
- Hurricane forecasting
- El Niño & La Niña forecasting
- Ship routing
- Offshore industries
- Fisheries management
- Marine mammal research
- Coral reef research
- Snow depth changes
- Tsunamis
- Etc......

See http://sealevel.jpl.nasa.gov/science/applications.html

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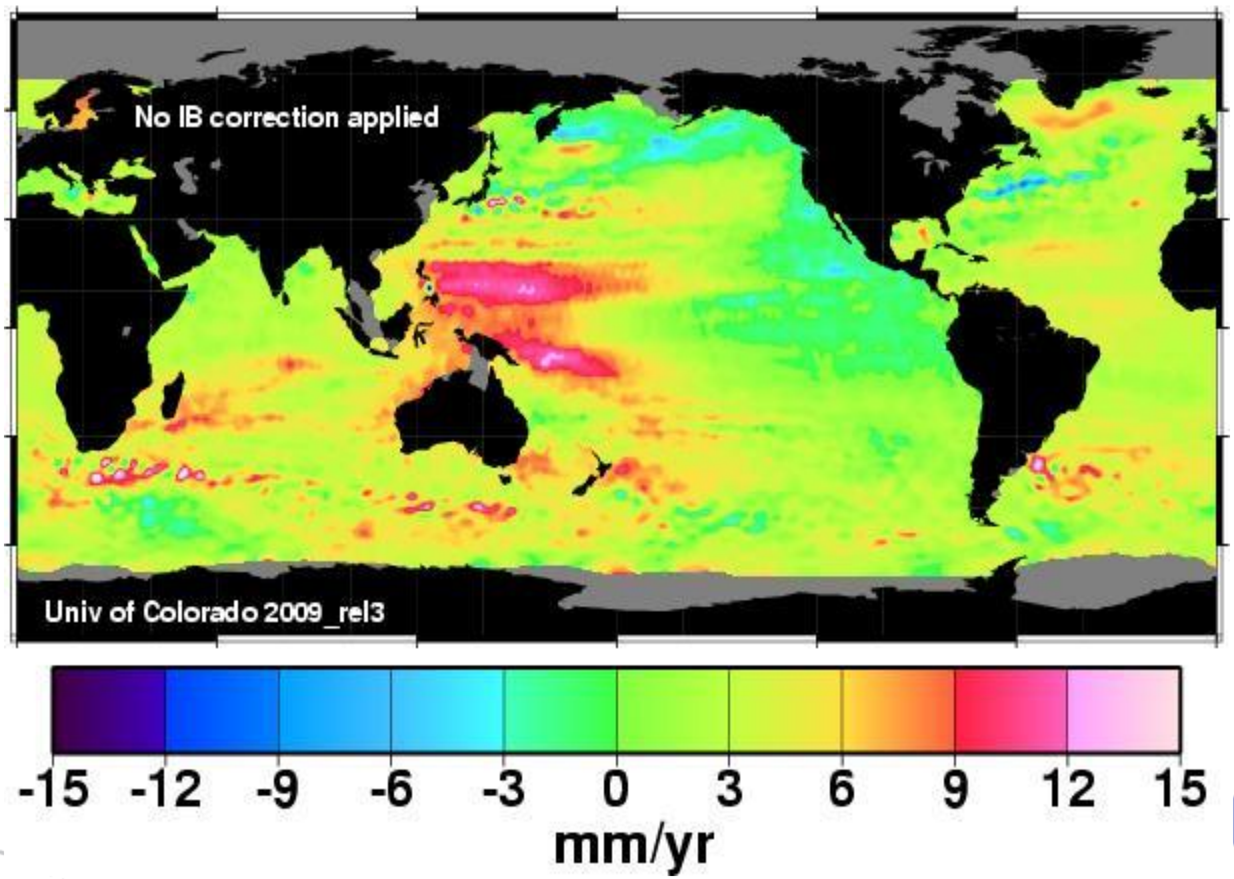
TOPEX/Poseidon and Jason-1 data are available at http://sealevel.colorado.edu/ and http://podaac.jpl.nasa.gov/.

Example: Climate -local trends in sea level



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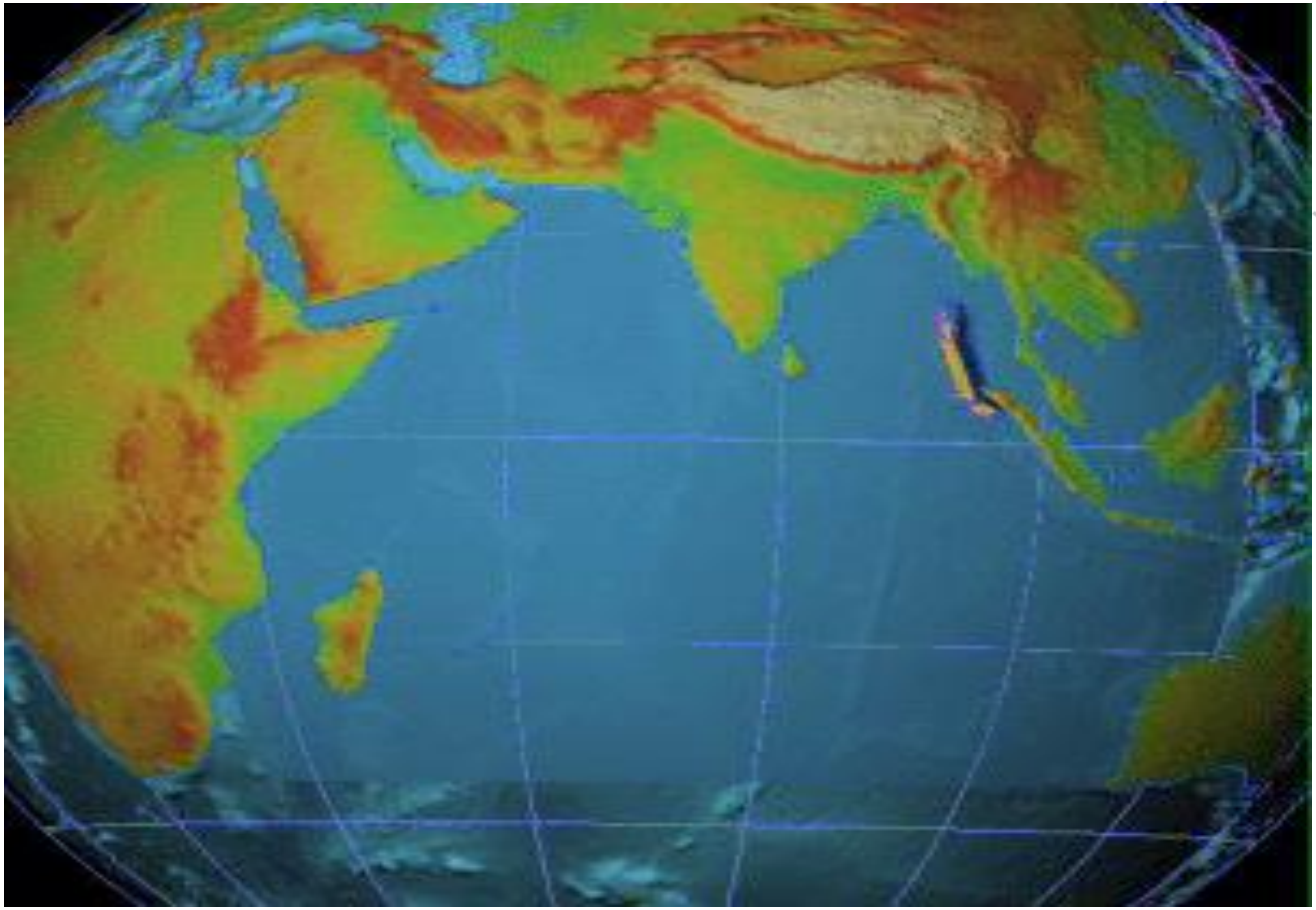
From http://sealevel.colorado.edu/

Example: Tsunami Indian Ocean 2004



Animation from NOAA:
National Oceanic and Atmospheric Administration

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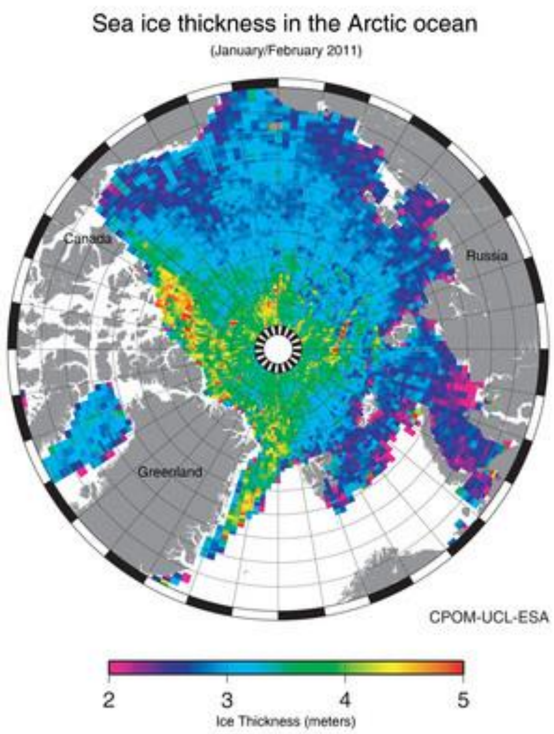
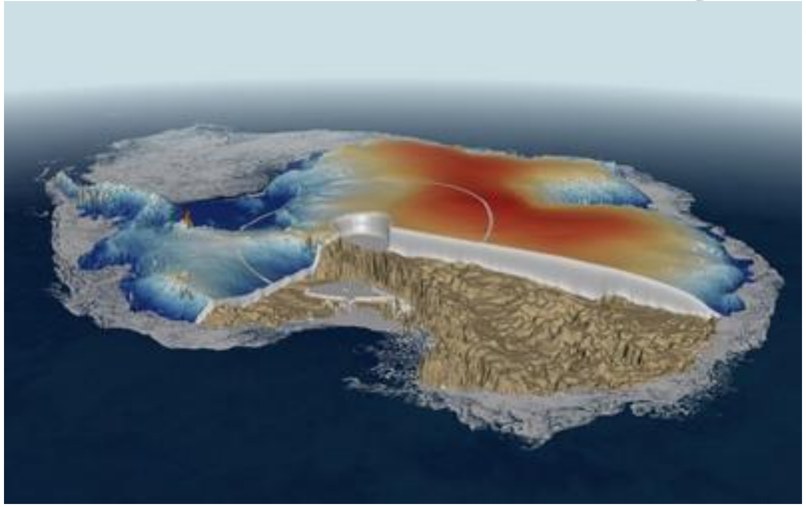
From http://www.noaa.gov/about-noaa.html & http://www.star.nesdis.noaa.gov/star/sealevelobservation.php & http://www.noaanews.noaa.gov/stories2005/s2365.htm

CryoSat – Ice thickness

ESA CryoSat mission: From an altitude of just over 700 km and reaching unprecedented latitudes of 88º, CryoSat has delivered precise measurements to study changes in the thickness of Earth's ice.



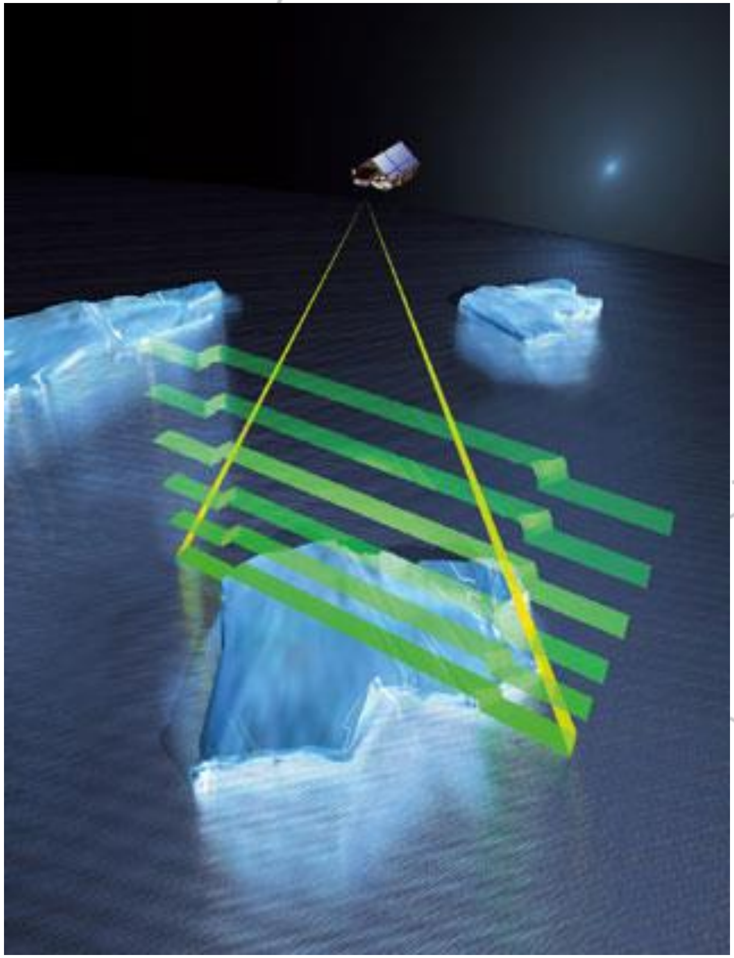


Cryosat was launched from Baikonur in April 2010.

http://www.esa.int/esaLP/SEMAAW0T1PG_LPcryosat_0.html

CryoSat technique

Measures not only the area of ice,
but the volume.
Radar altimeter measurements. It operates in SAR and Interferometric modes, hence the altimeter is called SIRAL
(SAR Interferometric Radar Altimeter)



The CryoSat-2 ground segment is organised around a single ESA ground station, located in Kiruna-Salmijarvi, in Northern Sweden.

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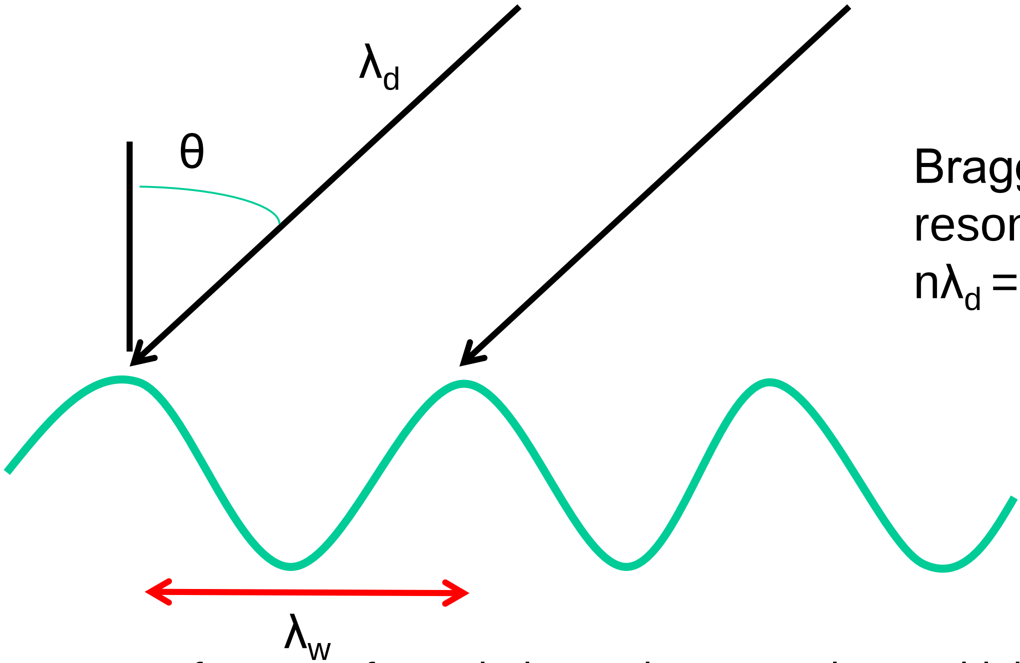
 http://www.esa.int/SPECIALS/Cryosat/index.html

Bragg scattering

- Technique
- Application with examples

Ocean wave and wind detection, Satellite scatterometer



Bragg's law:
resonance occurs when
$n\lambda_d = 2\ \lambda_w \sin\theta$

Measurements of near-surface wind over the ocean, by combining measurements from different azimuth angles, the near-surface wind vector over the ocean's surface can be determined using a geophysical model function which relates wind and backscatter.

The backscattered power from the waves depends on the wind speed and direction. Viewed from different angles, the observed backscatter from these waves varies. These variations can be exploited to estimate the sea surface wind, i.e. its speed and direction.

Scatterometer wind measurements are particularly useful for monitoring hurricanes.

Scatterometer data are applied to the study of vegetation, soil moisture, polar ice, and global climate changes.

They have also been used to measure winds over sand and snow dunes.

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Oil spill detection with Bragg scattering

- Oil spill will change the radar backscattering, and produce dark patches in the satellite images.
- However, several look-alike phenomena exist such as:
  - Natural ocean surface films
  - Rain cells
  - Ship wakes
- Detection is also difficult if there is no wind or very strong winds.

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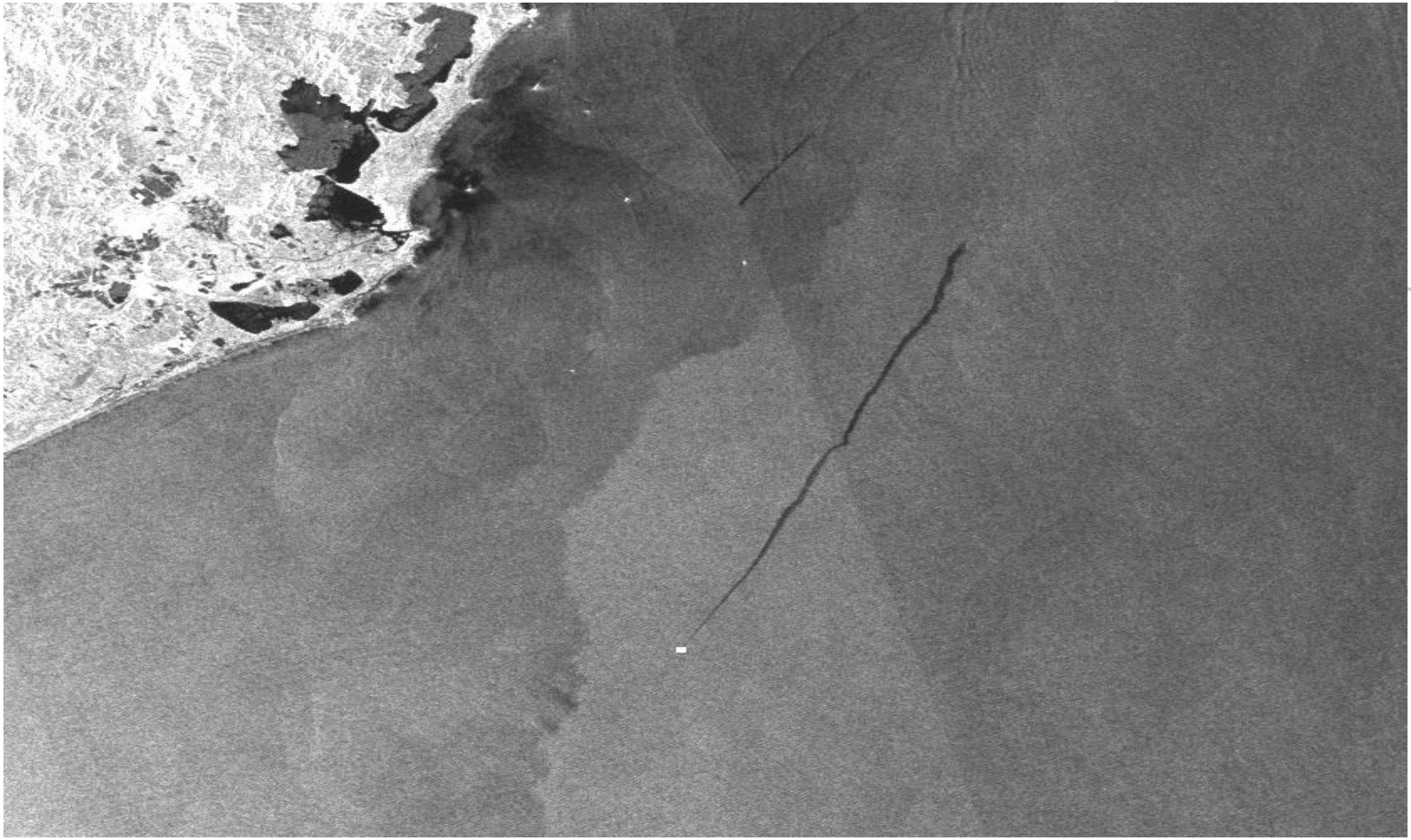
Example: oil spill outside Brazil



From http://www.ksat.no/Products/OilSpillDetection.htm

Passive techniques

- Photographic
- Radiometry
- Gravitational
- Spectral measurements of stars
- Infrared measurements from albedo
- Signal reception (AISsat)

Meteorology

Image credit: NASA/GSFC/LaRC/JPL, MISR Team

Hurricane Irene 27 Aug 2011.

Acquired by the Multi-angle Imaging SpectroRadiometer (MISR) instrument on Terra. MISR uses nine cameras to capture images of the hurricane from different angles.

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http://www.nasa.gov/mission_pages/hurricanes/archives/2011/h2011_Irene.html/

Radiometry

A passive radio obeservation technique - especially used for snow depth measurements.

As an example: microwave emission from a layer of snow over ground consists of two parts:

- emission by the snow volume
- emission by the underlying ground.

Both contributions are governed by the transmission and the reflection properties of the air-snow and snow-ground interfaces and by the absorption and scattering properties of the snow layer.

The advantage of radiometry vs. optical techniques is that the observation is weather independent as radio waves penetrate clouds.

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Radiometer AVHRR: http://www2.ncdc.noaa.gov/docs/klm/html/c3/sec3-1.htm

Example: ”Gravity maps show disastrous draining in India's breadbasket”

Article in IEEE Spectrum 12th AUG 2009

Scientists at NASA’s Goddard Space Flight Center and the University of California, Irvine, discovered the groundwater loss in new maps of the Earth’s gravity made using the twin satellites of the Gravity Recovery and Climate Experiment (GRACE) system.

Unlike most Earth-observing satellites, GRACE doesn’t infer properties of the Earth’s surface from emitted or reflected radiation. Instead, the two satellites orbit in tandem, maintaining a distance between them of 220 kilometers. As the twin satellites fly, minor perturbations in the Earth’s gravity fields may cause the lead satellite to accelerate slightly before pulling the trailing satellite along and resuming the prescribed 220-km distance. A microwave ranging system on board GRACE tracks the minute changes in distance, and Global Positioning System receivers can pinpoint the location of the satellites over Earth with high precision. By constantly measuring the distance between the two satellites, the system can generate sufficient data to produce maps of the Earth’s gravity anomalies each month. Any changes in the mass of the land beneath the satellites over time are reflected in subsequent flights over the region.

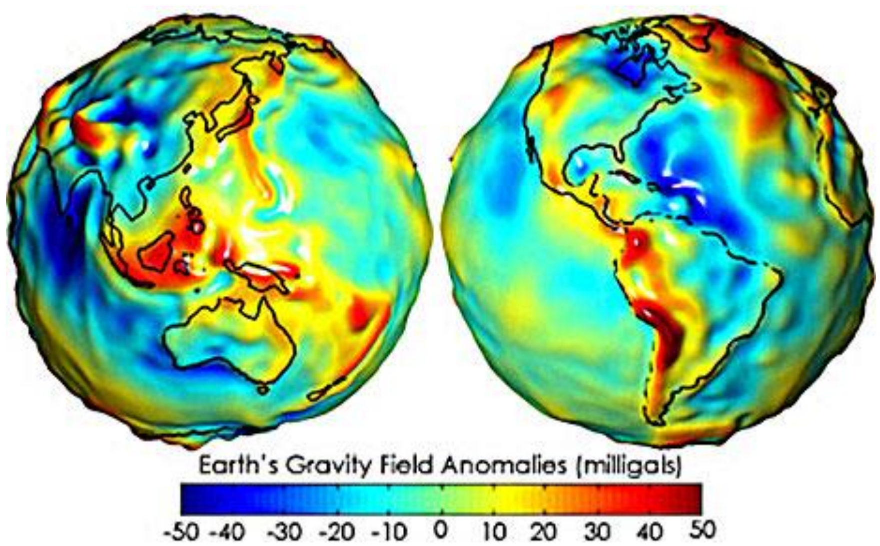

Illustration: NASA

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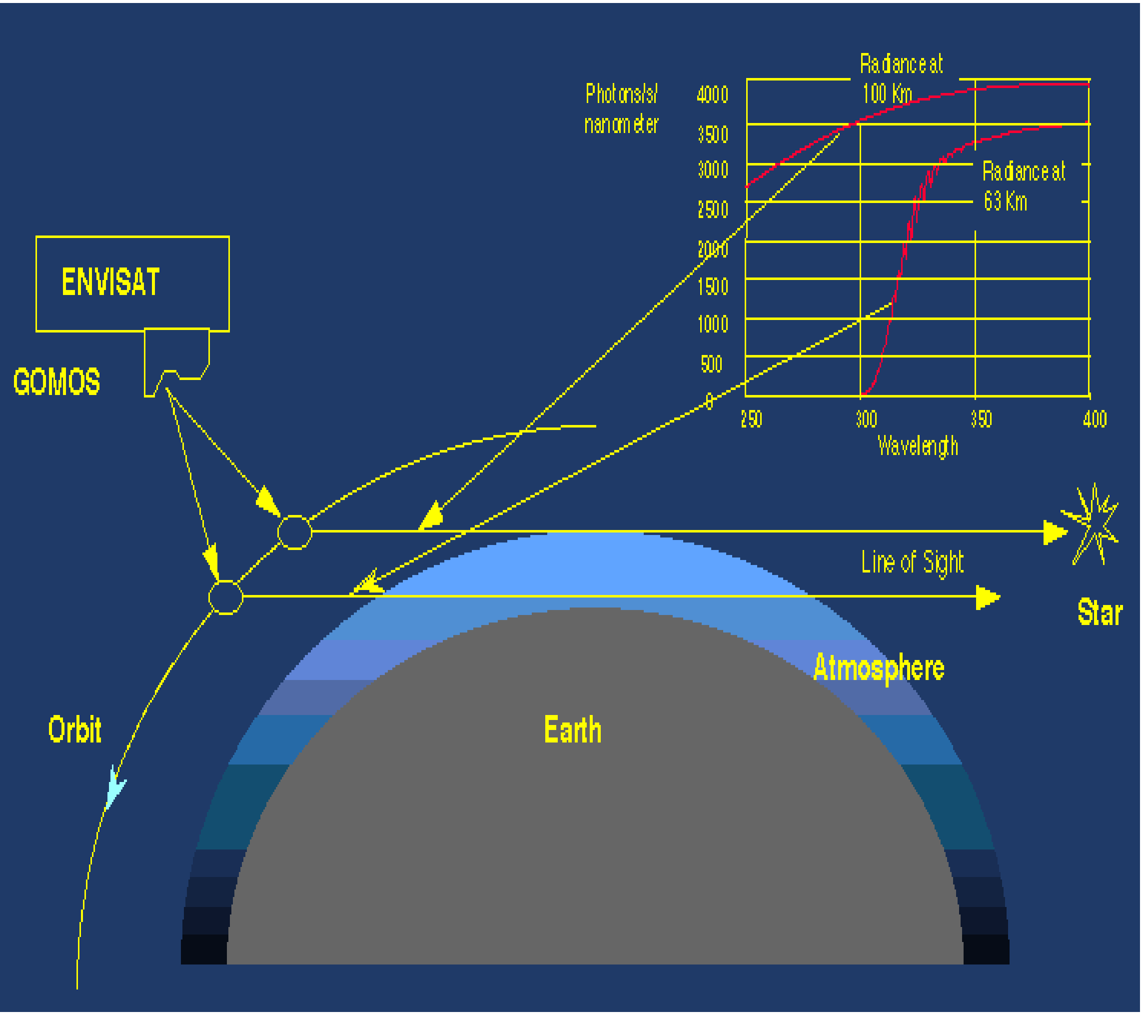
From http://www.spectrum.ieee.org/aerospace/satellites/satellites-peer-into-indias See also: http://www.nasa.gov/topics/earth/features/india_water.html

Example: GOMOS- Global Ozone Monitoring by Occultation of Stars



- From Envisat (ESA) launched 1 March 2002.
- The first space instrument dedicated to the study of the atmosphere of the Earth by the technique of stellar occultation.
- The electromagnetic spectrum of stars is used (ultraviolet, visible and the near infrared parts)
- Observation of ozone and related species in the middle atmosphere (15 to 100 km).
- The 250-680 nm spectral domain is used for the determination of O_3, NO_2, NO_3^-, aerosols and temperature.
- Two high spectral resolution channels centred at 760 and 940 nm allow measurements of O_2 and H_2O
- Two fast photometers are used to correct star scintillation perturbations and to determine high vertical resolution temperature profiles.
- Global latitude coverage is obtained with up to 40 stellar occultations per orbit from South Pole to North Pole.
- Data acquired night-time is of better quality than day-time data because of a smaller perturbation by background light.

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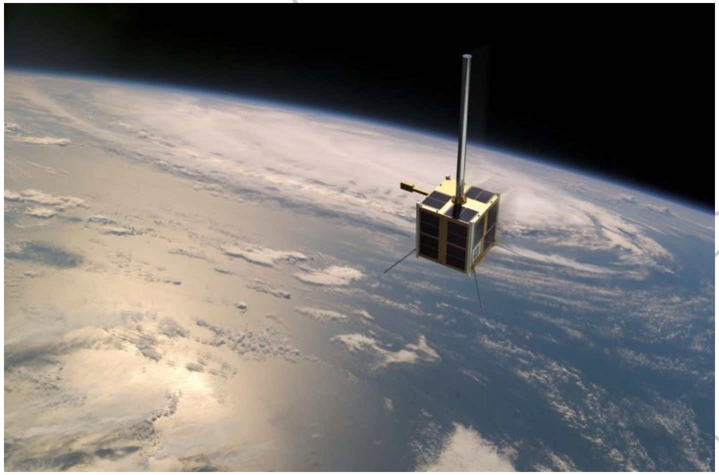
http://envisat.esa.int/instruments/gomos/ and http://wdc.dlr.de/sensors/gomos/sheet.php

AISsat characteristics



- Polar LEO orbit of 600km
- Nanosatellite 20cm x 20cm x 20cm, weight 6kg
- Launched by an Indian PSLV rocket from ISRO's facilities in Sriharikota on the 11th of July 2010
- VHF communication (30-300MHz)
- The Automatic Identification System (AIS) is a self-organizing TDMA radiocommunication system

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AISsat

- NRS (Norwegian Space Center) owns the project
- FFI (Norwegian Defense Research Establishment) is responsible for the technical implementation
- Kystverket (the Norwegian Coastal Administration) is the receiver of the information
- SFL (Space Flight Laboratory at the University of Toronto Institute of Aerospace Studies) has provided the spacecraft platform and the AIS VHF antenna
- The payload is being developed by Kongsberg Seatex AS with oversight from FFI.
- Kongsberg Satellite Services AS is providing the Earth station facility.

Forsvarets forskningsinstitutt

Norsk Romsenter
NORWEGIAN SPACE CENTRE

University of Toronto Institute for Aerospace Studies
Space Flight Laboratory
"Building Canada's Future in Space..."

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AISsat

AIS is required on every seagoing vessel of 300 gross tons or more, and on all passenger vessels.

Animation provided by Norsk Romsenter/FFI/Kystverket/Seatex

Navigation, GPS

- Global satellite navigation system developed by US DoD
- Constellation of between 24 and 32 MEO satellites
- Determination of location, time and velocity
- A variety of applications, also for synchronisation (earth quakes, cellular networks...)

History

- Tested successfully in 1960 – 5 satellites
- Based on similar principles as the ground-based LORAN system used in WW II
- Discovery of how Doppler shift can be exploited (Sputnik 1957)
- Ronald Regan decided to make GPS freely available for civilian use after Korean Air Lines flight was shot down in USSR prohibited airspace due to navigation errors in 1983
- Fully developed system with satellites launched between 1989 and 1993
- Initially the signal available for civilians was intentionally degraded. This ended in 2000 -> precision improved from 100m to 20m

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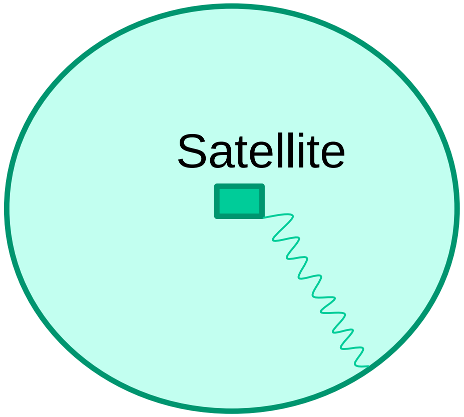
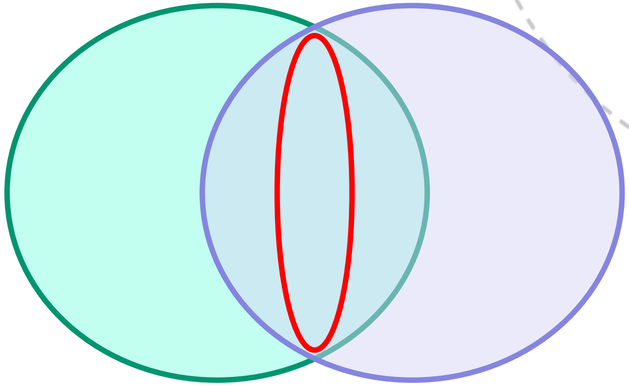
Basic principles

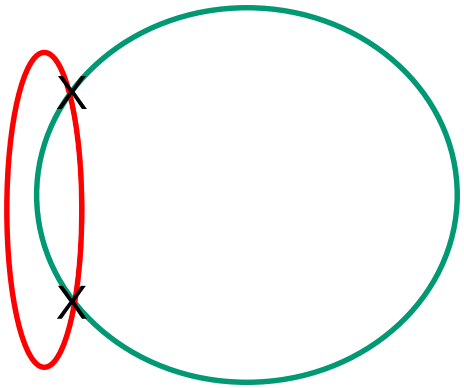
Need 3 satellites to give 3 co-ordinates in space



Location sphere



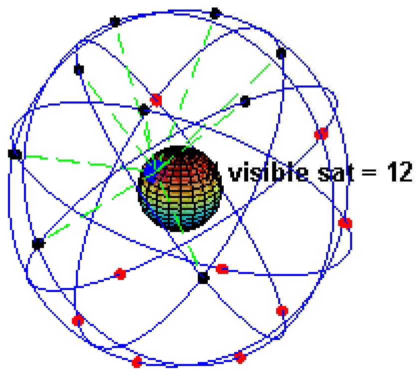
2 satellites, location circle



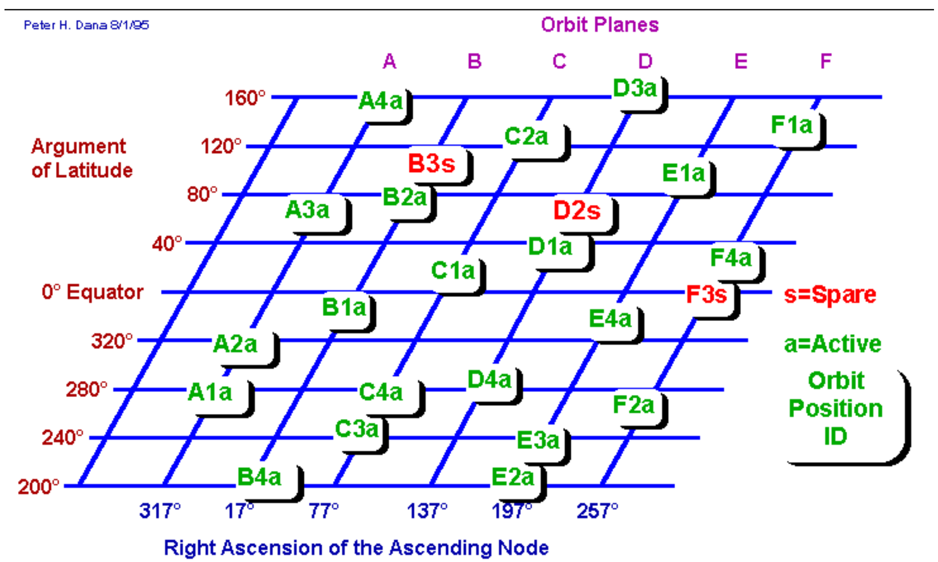
3 satellites, two location points

The use of a fourth satellite will give the fourth dimension; time information

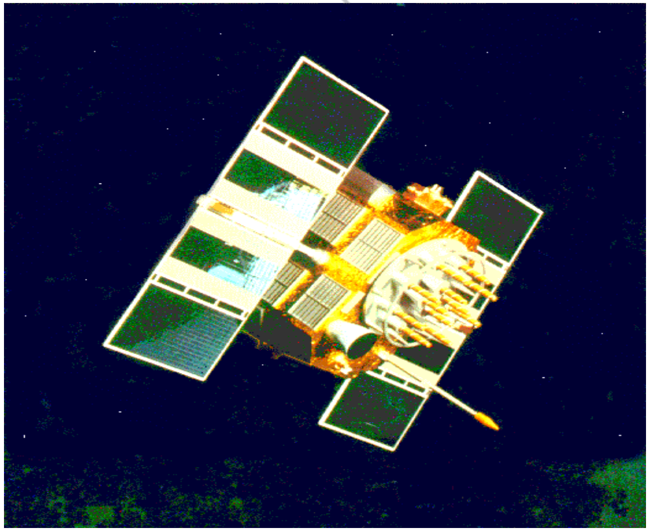
GPS constellation



24 satellites in 6 orbital planes
4 satellites in each plane
Altitude: 20200km, 55° inclination



Simplified Representation of Nominal GPS Constellation



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Time information

- Used to correct the receiver's clock as GPS receivers do not have high quality clocks in order to make mass marked products affordable
- Used in other application such as cell phone base stations, traffic signal timing, time transfer etc.

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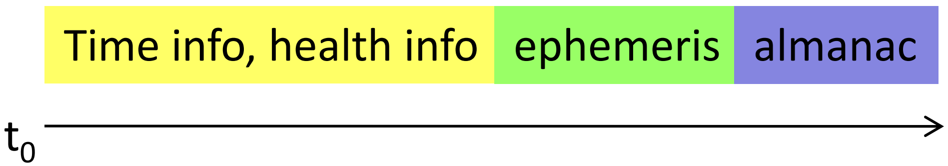
Navigation signals

A navigation message is broadcasted at 50bit/s



Frame length 1500 bits -> frame duration 30 sec.
t_0 is precisely every minute and half minute

Frame (F) -> 5 subframes (SF) -> 10 words (W) of 30 bits:

- W1-W2 in every SF: telemetry (UW)
- SF 1, W3-W10: satellite clock and relation to GPS time
- SF2-SF3, W3-W10: ephemeris data giving the satellite's precise orbit, updated every 2 hour and valid for 4 hours
- SF4-SF5, W3-W10: partial almanac (1/25) for the rest of the constallation

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Transmitter caracteristics

- Tx frequency: 1.57542 GHz (L1) and 1.2276 GHz (L2)
- The L1 frequency carries the navigation message and the Standard Positioning Service code signals.
- The L2 frequency is used to measure the ionospheric delay by Precise Positioning Service equipped receivers.
- CDMA spread spectrum, each satellite uses a unique PRN code
- Two CDMA encodings:
  - Coarse/Aquisition (CA) Gold code 1.023Mchips/s for the L1 carrier
  - Precises (P) code 10.23Mchips/s for the L2 carrier
  - Military Precise code (P(Y))

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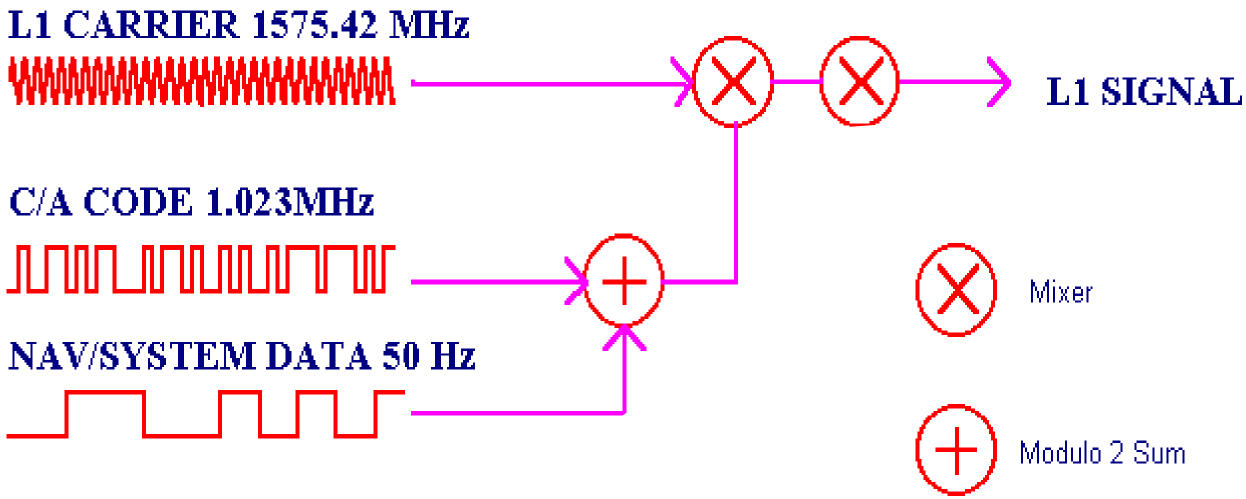
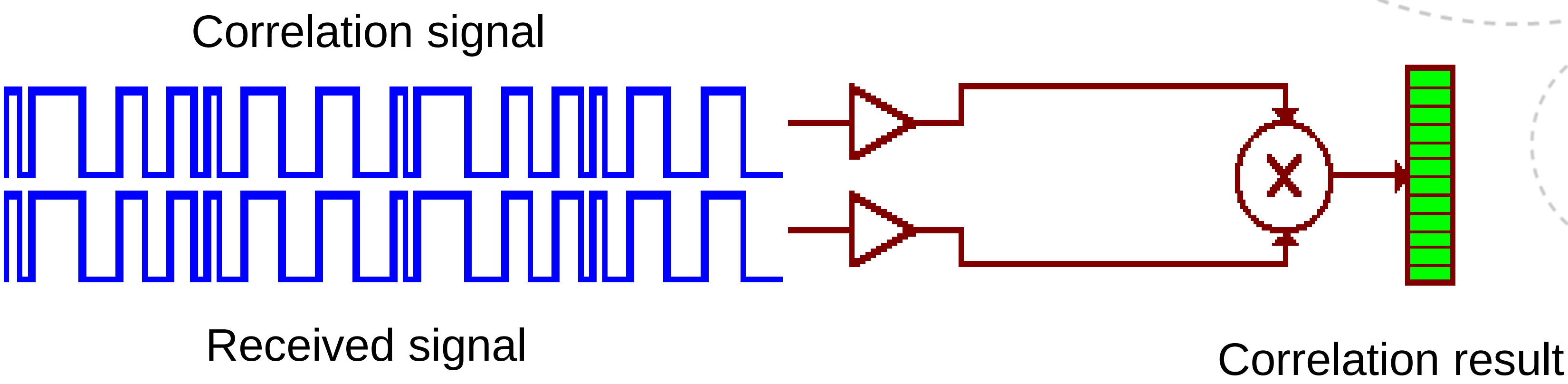
GPS signal transmission



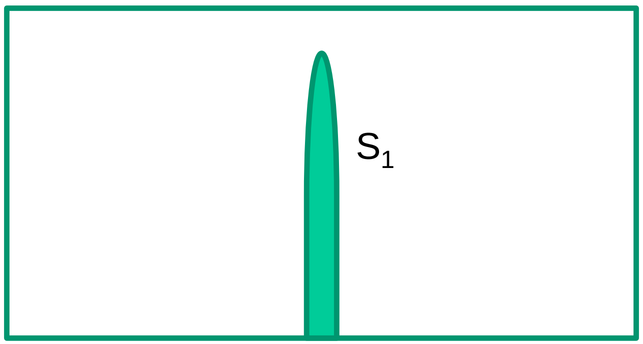
From http://www.colorado.edu/geography/gcraft/notes/gps/gps.html by P.H. Dana

PRN correlation



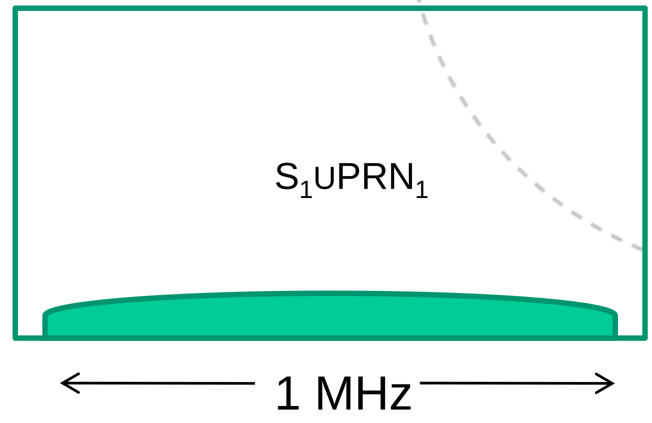
CDMA spread spectrum

Signal spectrum before PRN coding

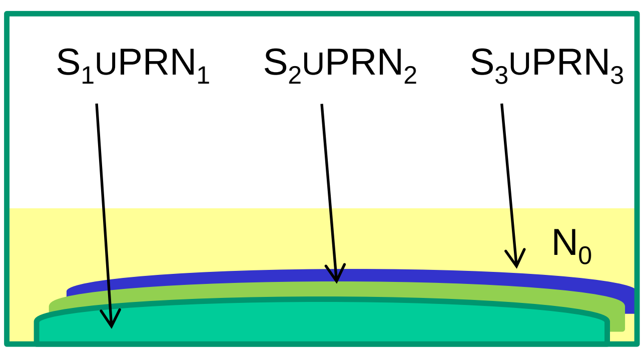


50 Hz

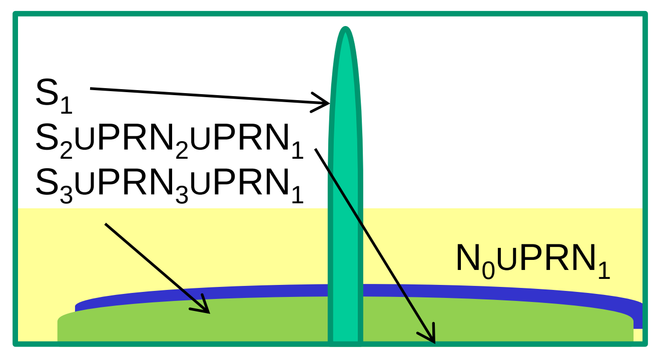
Signal spectrum after PRN coding



Signal spectrum at reception



Signal spectrum after correlation



Challenges

- Reference system
- Error sources
- Orbits
- Signals

The reference problem

- Shape of the earth
- Spinning of the earth
- Moving north pole (z-axis)
- Precession and nutation
- Plate tectonics

➢ A location is linked to time

7 basic units of measurement

- The meter
- The kilogram
- The second
- The kelvin
- The mole
- The ampere
- The candela
- ➢ Of the seven basic units, only time is changing

How to define 1 second?

- Linked to earth's rotation around the sun – solar day
- Linked to earth's rotation with reference to fixed stars – sidereal day
- But the earth spin is not constant, it is slowing down by 1s per year, in addition to random changes due to tides, wind friction, earth quakes*, plate tectonics etc.
- Atomic time – linked to the radiation of a Cesium-133 atom transiting between two ground states with a very fine spectral line. Must still link it to earth's rotation. TAI (International Atomic Time) becomes UTC (Coordinated Universal Time). UTC needs leap seconds.

*see http://www.space.com/11115-japan-earthquake-shortened-earth-days.html , «How the Japan earthquake shortened days on earth». The earthquake, 8.9-magnitude, on the 11.03.2011 accelerated the spin of earth by 1.8μs. A time error of 1.8μs gives a GPS position error of 540m.

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GPS time (GPST)

- Defined on the basis of a set of atomic clocks in the ground stations and onboard the satellites
- A real-time clock
- No leap seconds
- $\Delta(GPST,UTC)_{1^{st}\ Jan\ 2010} \approx 15s$
- GPST is steered to remain within 1μs [mod 1s] of UTC
- Time corrected once pr. day from Master Control Station, and error fraction is kept within 5-10ns (10ns corresponding to a range error of 3m).
- Corrections also have to account for relativistic effects and the orbit not being perfectly circular. This gives a time dependent correction of 0-45ns depending on the satellite's position in the orbit.

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The GPS orbit = the ephemeris

The ephemeris is defined by 16 parameters, and they are broadcast by the satellite

	SV 06	
t_e [s]	1.295840E+05	Ephemeris reference time
$\sqrt{a}$ [$\mathrm{m}^{1/2}$]	5.153618E+03	Square root of semimajor axis
e	5.747278E-03	Eccentricity
M_0[rad]	-2.941505E+00	Mean anomaly at reference time
ω_0[rad]	-1.770838E+00	Argument of perigee
i_0[rad]	9.332837E-01	Inclination angle at reference time
l_0[rad]	2.123898E+00	Longitude of ascending node of orbit plane at weekly epoch
Δn [rad s^{-1}]	5.243075E-09	Mean motion difference from computed value
i [rad s^{-1}]	-6.853856E-10	Rate of inclination angle
$\dot{\Omega}$ [rad s^{-1}]	-8.116052E-09	Rate of right ascension
C_{uc}[rad]	-1.184642E-06	Amplitude of cosine harmonic correction term to the argument of latitude
C_{us}[rad]	7.672235E-06	Amplitude of sine harmonic correction term to the argument of latitude
C_{rc}[m]	2.146562E+02	Amplitude of cosine harmonic correction term to the orbit radius
C_{rs}[m]	-2.140625E+01	Amplitude of sine harmonic correction term to the orbit radius
C_{ic}[rad]	2.980232E-08	Amplitude of cosine harmonic correction term to the angle of inclination
C_{is}[rad]	-1.117587E-08	Amplitude of sine harmonic correction term to the angle of inclination

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Ideal range measurement

The range from the satellite to the receiver is

$r = c \cdot (t_r - t_t)$

where t_r is the reception time and t_t is the transmit time stamped on the signal by the satellite transmitter.

Code phase measurement

- The time references are not synchronised => the range becomes a pseudo-range.
- The satellite has one time reference, the receiver another, and the GPS system yet anoter (the true time).
- The code phase is read as an analogue clock, hour, minutes and seconds; or Z-count + number of navigation bits transmitted + number of C/A-code repeats + number og whole C/A-code chips + fraction of C/A-code chip.

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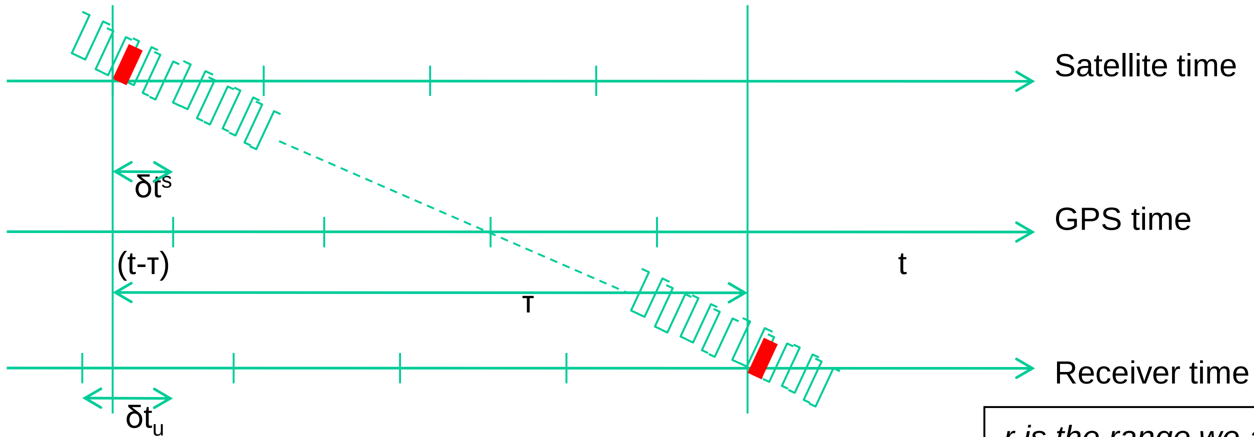
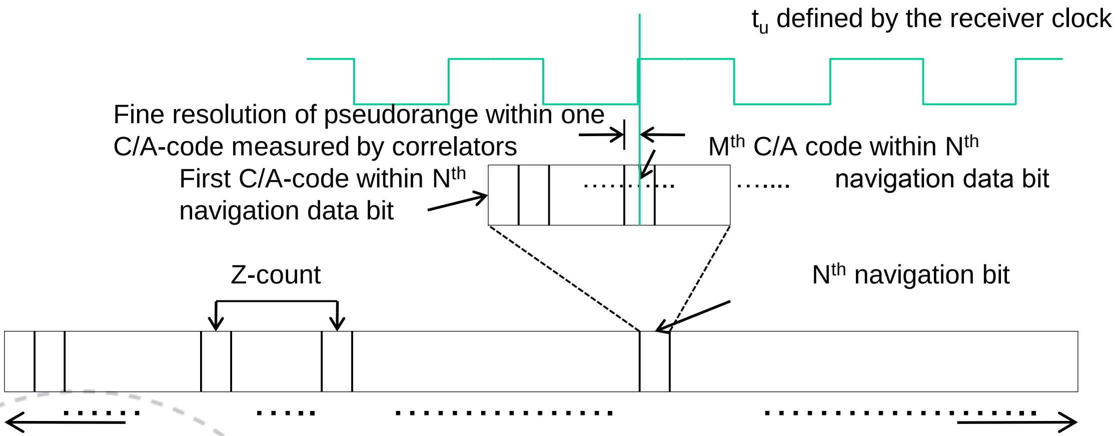
Code phase measurements



Pseudorange $\rho = r + c[\delta t_u - \delta t^s] + I + T + \varepsilon$

r is the range we are looking for
c is the speed of light in vacuum
I is the ionospheric delay
T is the tropospheric delay
ε is any other noise



one subframe (6 seconds, 300 navigation data bits)

The satellite time $t^s = (t-\tau) + \delta t^s$ = Z-count
+ number of navigation bits transmitted
+ number of C/A-code repeats
+ number og whole C/A-code chips
+ fraction of C/A-code chip

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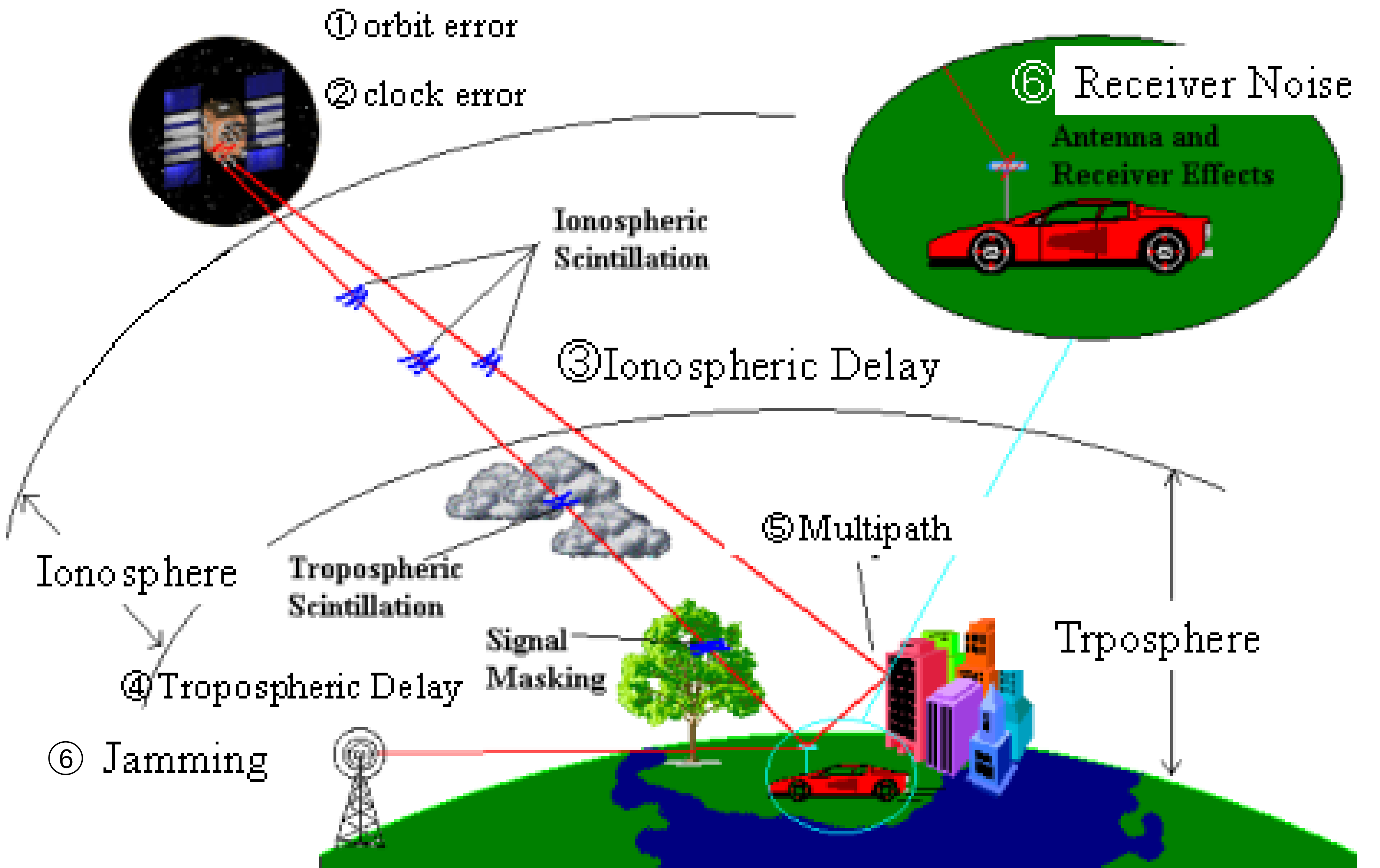
Errors on GPS Signal



Summary

- LEO satellites for earth observations
- MEO satellites for navigation
- Spectral atmospheric windows
- Poor resolution for radio signals => techniques to improve the resolution:
  - Synthetic aperture
  - Pulse compression (chirp signals, spread spectrum)
- Observation techniques (summary next slide)
- Data storage/transfer compromise
- Navigation parameters is a main component to the observation techniques

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Summary observation techniques active and passive

- Interferometry
- Altimeters (RADAR, LIDAR)
- Bragg scattering
- Radiometry
- Gravitational force deviation
- Spectral changes for star occulation
- Optical IR sensors

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