SPACE WEATHER INTRODUCTORY COURSE

SWIC

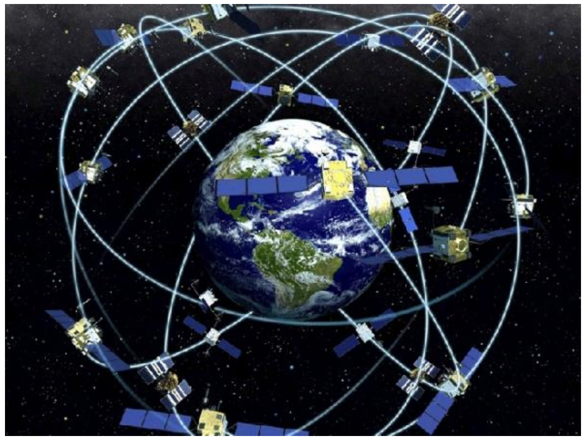
Collaboration of:

Solar-Terrestrial Centre of Excellence

Koninklijke Luchtmacht

Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

May 2017



IMPACT ON GPS

Basics of GPS & how it is disturbed by SPWX

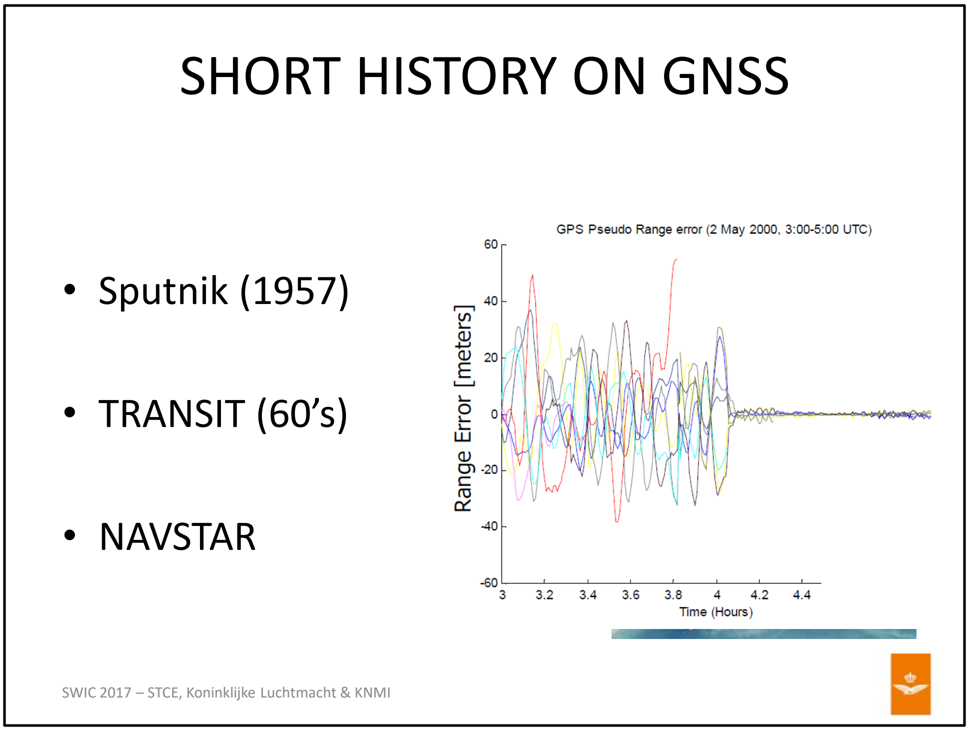
Willem-Pieter van der Laan

CREDITS & THANKS TO

- Ir. Barend Lubbers (FMW, NLDA)
- US Air Force 557th Weather Wing
- "*The influence of the ionosphere on GPS Operations*" by Mihail Codrescu, SWPC
- Wikipedia

OUTLINE

- Introduction
- GPS segments
  - Space
  - Ground
  - User
- Sources of error
  - SPWX related
    - Ionospheric delay
    - Ionospheric scintillation
    - Solar radio bursts
  - Not SPWX related
    - Jamming
    - Spoofing

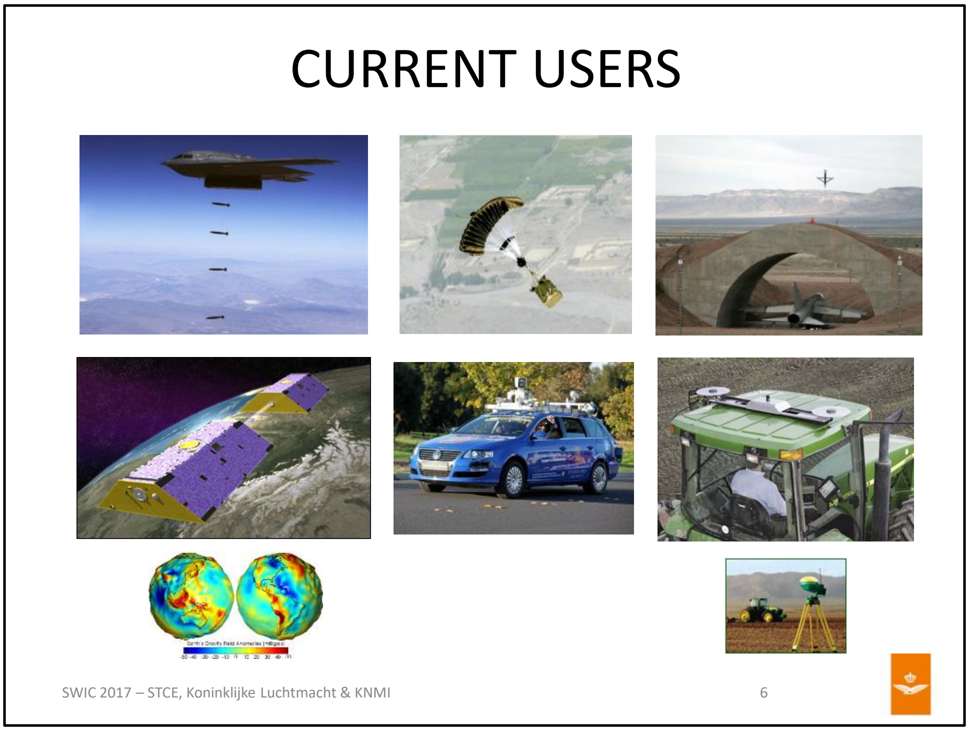


PNT has always had the interest of merchant ships and navy as there are no recognition points at sea. Noem plaats & tijdsbepaling. Leg link met marine/koopvaardij. Van aarde naar ruimte.

In 1957 the US tracked the Sputnik. Using Doppler shift they could calculate its orbit. Then it was thought: why not invert the calculations? So, if we know the orbit of a satellite and can track it, we can calculate our position. That gave birth tot TRANSIT.

TRANSIT were 5 satellites (with 5 back-ups) that allowed position calculation once every few hours. It was intended for the submarines and became the precursor of NAVSTAR GPS. After the flight accident with Korean Air Flight 007 in 1983, then president Reagan released GPS for civil use. With intentional noise, so the military stayed ahead in precision.

On 2 May 200 around 04:00 UTC president Clinton switched off the selective availability mode (the intentional noise) thereby improving civil accuracy from 100’s m to 10’s m. That boosted the civil use.



GPS has become a global utility. The GPS user segment is unique in that it must satisfy the requirements of both the U.S. Military and civil users.

Upper row: military applications, lower row: civil applications.

B2 Spirit dropping Joint Direct Attack Munitions (JDAM)

- XX 500lb GBU-38 (INS-GPS)
- XX 2000LB GBU-31 (INS-GPS) on a Rotary Dispensing System
- New versions have AJ antenna/electronics in the tail kit
- Minimizing duration of "bay doors open" is a key employment consideration

Joint Precision Airdrop System (JPADS)

- Guides parachute to designated coordinates
- Reusable. Older GPS only/ newer GPS-INS. Connected to a Laptop sized controller

Small Diameter Bomb

- Designed to use augmentation of GPS signal to further refine accuracy.
- Feds through link-16 to correct/update receivers
- As if, GPS uploaded all satellites with fresh data

Gravity Recovery and Climate Experiment (GRACE). March 2002.

- Two satellites in Low Earth Orbit. One lead/ one trail. Using
- Microwave beam measures distance between 2 spacecraft
- Mapped gravity picture of the earth. Profound impact on geodesy to include targeting

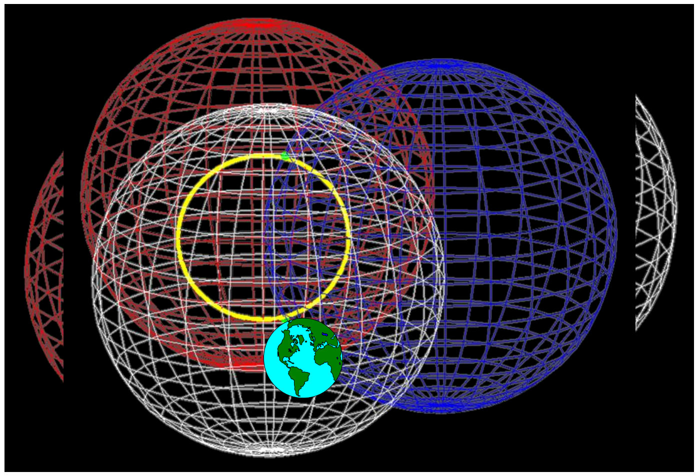
Autonomous car by VW.

Precision Farming

- Can achieve 2cm accuracies with augmentation systems
- Using Auto-steer system
  - Prevents blade/spray over runs
  - Operator monitors instead of drives
- By sampling soil with GPS coordinates
  - Can create a fertilizer spray pattern
  - Measure crop yields precisely
- Agricultural, Automotive, and Shipping Applications

HOW GPS WORKS

Trilateration



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The principle behind GPS is trilateration: calculate a position by measuring distances and use the geometry of circles. Measuring the distance to a GPS satellite is done by measuring the travel time of its signal and multiply this with the speed of light. The satellite's position is calculated from the message it transmits. Seeing 3 satellites at the same time, allows one to calculate its own position in 3D. However, time is of the essence.

HOW GPS WORKS

Trilateration + Timing = 4 satellites

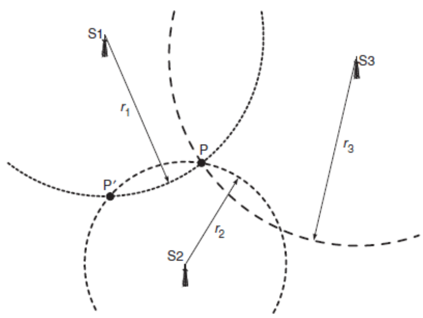

Figure 1.5 Trilateration.

An timing error of 1 ms gives a position error of 300 km! The satellite clocks are atom clocks, they run accurately. The receiver has a simple, quartz clock. If you don’t want to carry a heavy accurate clock, you have to see another satellite and use this one to correct the error in the receiver clock.

Resumé: to solve an equation of 4 unknowns (3 coordinates, 1 time), you need at least 4 satellites.

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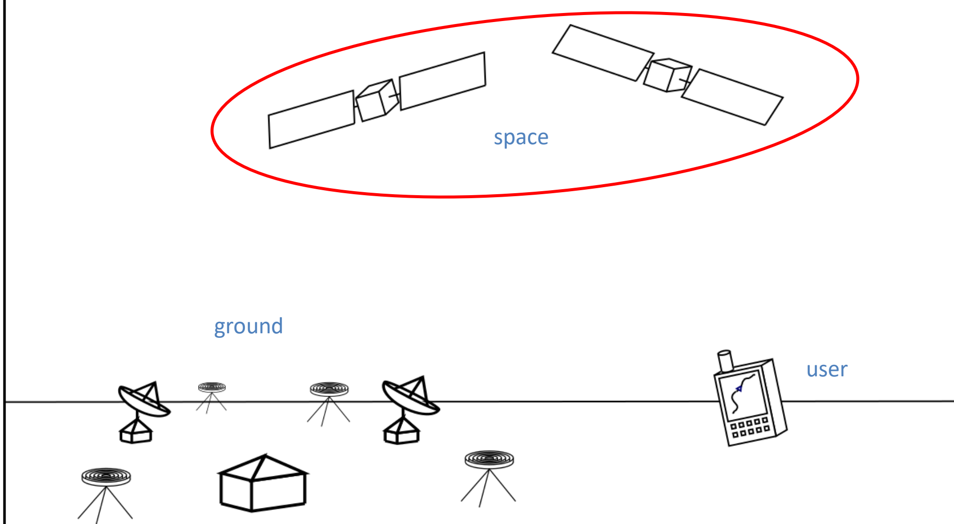
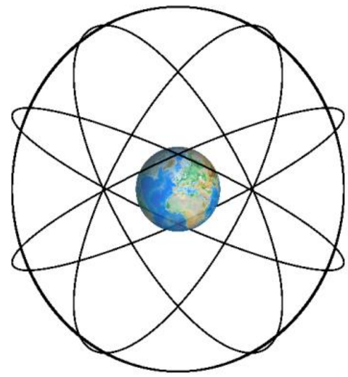
GPS SEGMENTS



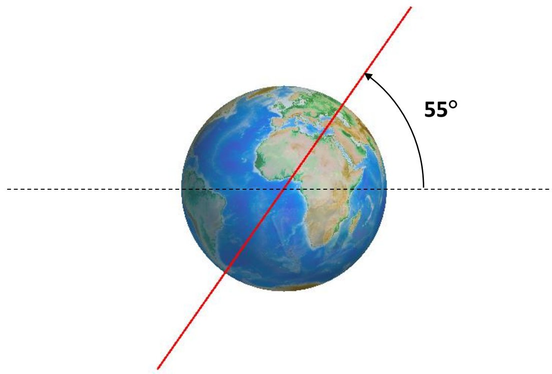
SPACE

- 32 satellites (24 nominal)
- 6 orbital planes
- Inclination 55°
- Orbit radius 26.560km
- Heigth ~20.000km
- Period 11h58m (12h siderial)



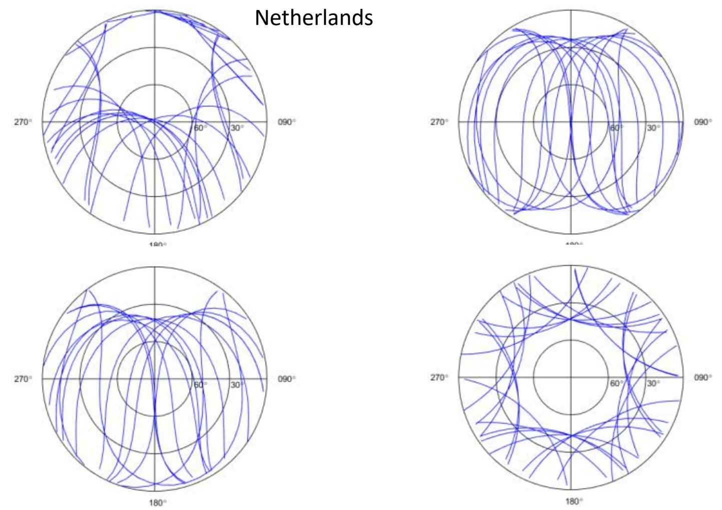
Some facts.

INCLINATION



Remember inclination.

AZIMUTH & ELEVATION



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Azimuth: horizontal direction. Elevation: heigth above the horizon.

The inclination of 55 degrees leaves a hole over the poles. Satellites will never have a high elevation there, though position calculation is not compromised.

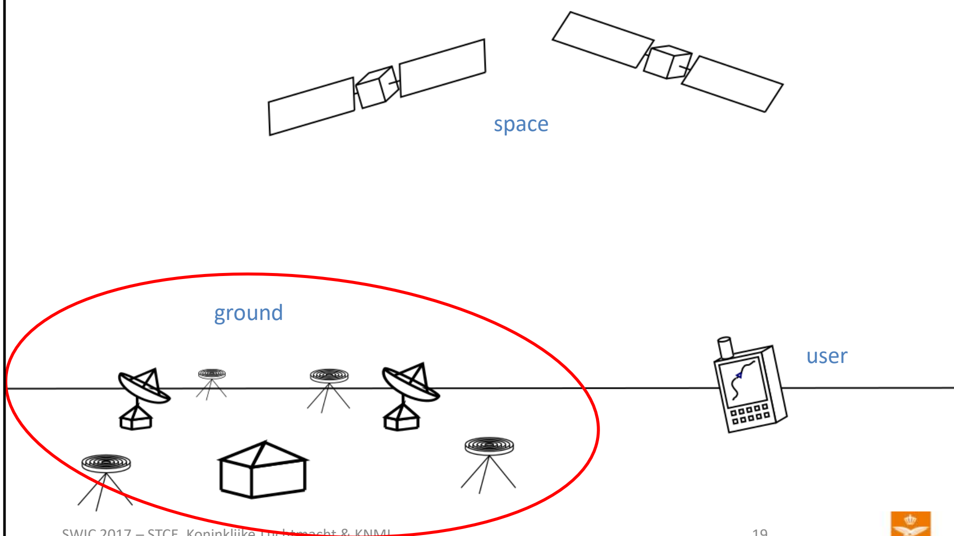
GPS SIGNALS (LEGACY)

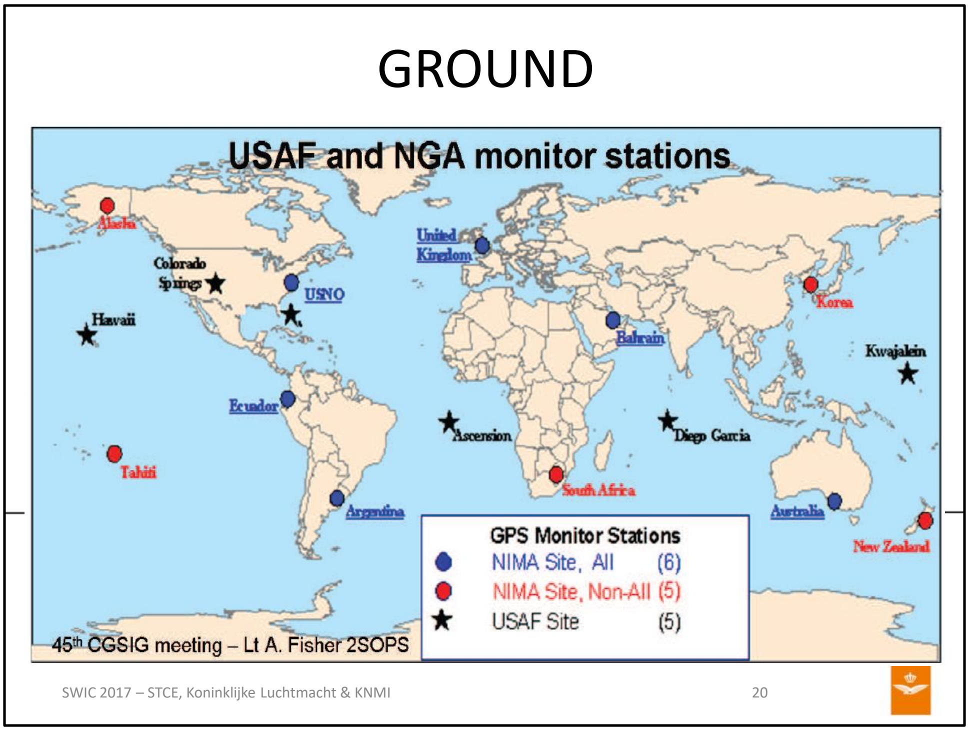
- 2 frequencies:
  - L1 (1575.42 MHz)
  - L2 (1227.60 MHz)
- C/A (Standard Positioning Service SPS):
  - On L1
  - Open to all users
- P(Y) (Precise Positioning Service PPS):
  - On L1 en L2
  - For military use only

C/A: course acquisition → first estimate, within which a receiver can search for the P-code. C/A: refreshes every millisecond. P(Y): refreshes every week.

P(recision) (Encr)Y(pted) → longer code, needs more time to fix, requires an encryption key, used by military. Applied in hostile environments against jamming and spoofing and for higher accuracy in position and timing. E.g. accurate timing is needed for frequency hopping between radios.

GPS SEGMENTS



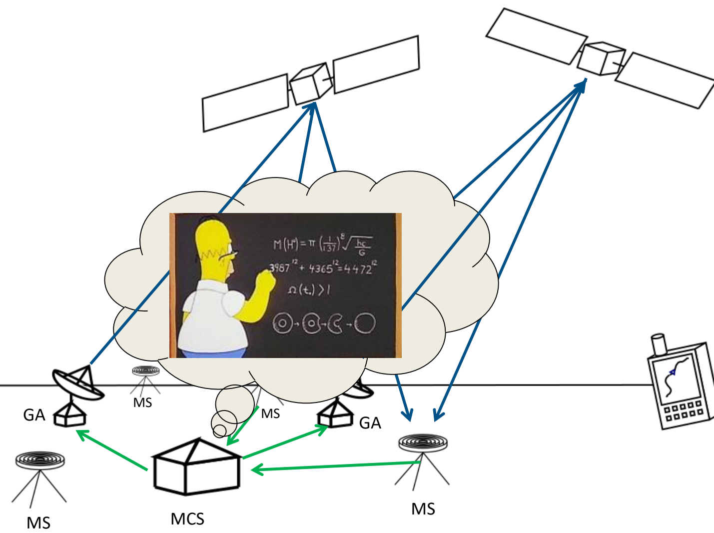


- Orbit control
- Calculate orbit correction commands
- Check integrity satellites
- Calculate almanac and ephemeris (update message)
- Maintain GPS time
- Calculate the correction of satellite clock errors

Ephemeris data: used to calculate the position of each satellite in orbit.
Almanac: information about the time and status of the entire satellite constellation.

NIMA: National Imagery and Mapping Agency
NGA: National Geospatial-Intelligence Agency
USNO: United States Naval Observatory

GROUND



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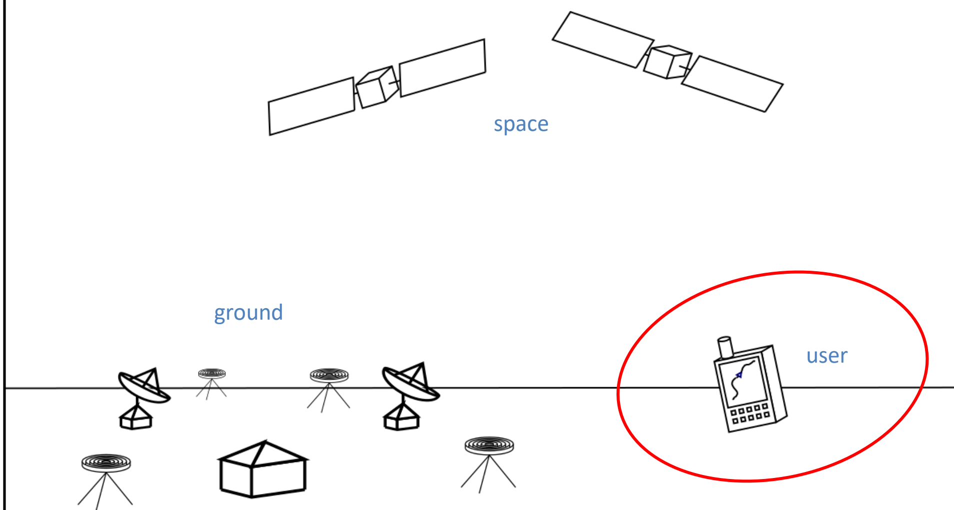

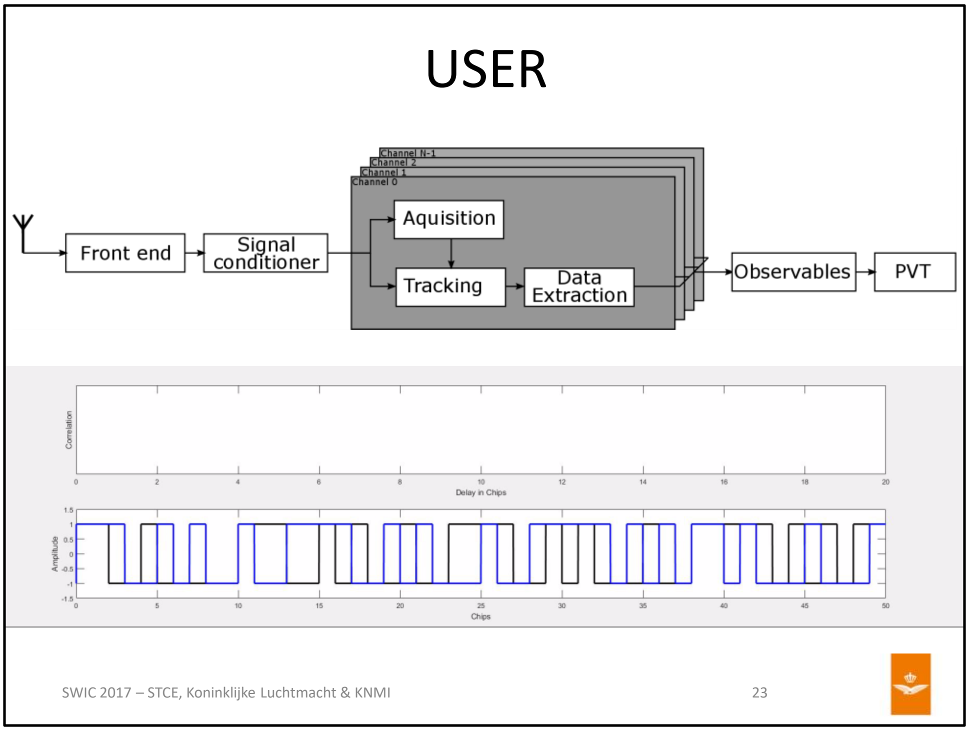

Front end: analoge signaal wordt omgezet naar digitaal.
Signal conditioner: zorgt ervoor dat het signaal door de ontvanger gegeten wordt/ermee kan werken.
Channel: maakt PRN aan en gaat correleren, houdt daarbij rekening met Dopplerverschuiving, geeft ruwe schatting van code-offset → dat gaat naar de **tracking-module** en die gaat fine-tunen. Zo wordt de PRN netjes opgelijnd, alsook de frequentie. Dan wordt in de **Data Extraction** “de PRN eruit gefilterd” (vermenigvuldigen met PRN) en de data eruit gehaald. Dan heb je de looptijd, je weet de positie van de satelliet (baanparameters) etc. (dit zijn de observables) en daarmee bereken je vervolgens Position, Velocity en Timing.

ALGEMENE UITLEG
Het zendschema en het uitgezonden signaal van de satellieten is bekend. De ontvanger genereert hetzelfde signaal op dezelfde tijd. Het signaal van de satelliet komt echter met een vertraging (de looptijd) aan. Als de ontvanger het signaal dus met een vertraging gaat genereren zodanig dat het ontvangen en gegenereerde signaal gelijk zijn aan elkaar, is de looptijd bekend

BOVENSTE PLAATJE
Signaal komt binnen bij het Front end, deze zorgt er samen met de signal conditioner voor dat het signaal digitaal en bruikbaar wordt voor de rest van de ontvanger. Vervolgens gaat het signaal naar de acquisition (uitgelegd in de volgende slides).

Als acquisitie succesvol is, geeft deze kenmerken door (prn, code fase en frequentie) aan de tracking loop.
Tracking loop neemt over een gaat het signaal tracken/volgen.
Uit de tracking loop komen de looptijden deze worden vervolgens omgerekend naar pseudoranges en gecorrigeerd voor systematisch fouten etc.
Pseudoranges worden gebruikt om de positie, snelheid en tijd uit te rekenen.

ONDERSTE PLAATJE
Ontvanger repliceert de signalen van de satellieten en correleert deze met het inkomende signaal. Correlatie geeft een piek bij perfecte oplijning van de twee signalen, daarbuiten zeer lage correlatie.

OVERIGE
Het ontvangen vermogen is ongeveer -160 tot -155 dBW.
De vermogensdichtheid is dan ongeveer -220 dbW/Hz.
De vermogensdichtheid van de ruis zit rond de -200 dBW/Hz. Het signaal zit dus 20dB lager! De vermogensdichtheid van de ruis is dus 100 keer groter dan de vermogensdichtheid van het GPS signaal!

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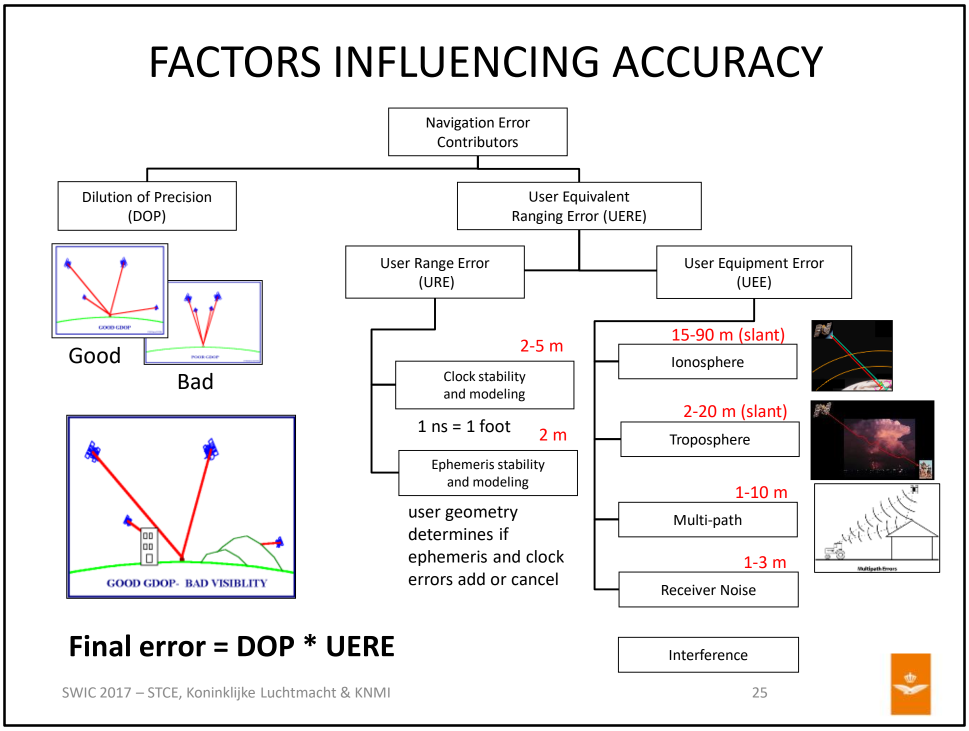


Equipment: clock, ephemeris, receiver noise.

Environment: ionosphere, troposphere, multipath, interference.

Things that effect GPS quality can be bucketed into geometry related things (DOP) and signal related things (UERE)

DOP x UERE = Solution Error

Users can have good geometry or bad geometry

Constellation is balanced through long term D-V planning

Unexpected outages can effect availability

Users can appear to have good geometry, from a planning perspective, yet due to obstacles have:

poor geometry

insufficient satellites for a solution

URE is managed by the control segment

Accuracy of Satellite Vehicle (SV) clock offset from GPS time

Accuracy of SV ephemeris

Depending on User location to a given satellite

Clock/Ephemeris errors can either add or cancel

UEE is determined by the individual user

Ionosphere – Single vs Dual frequency user

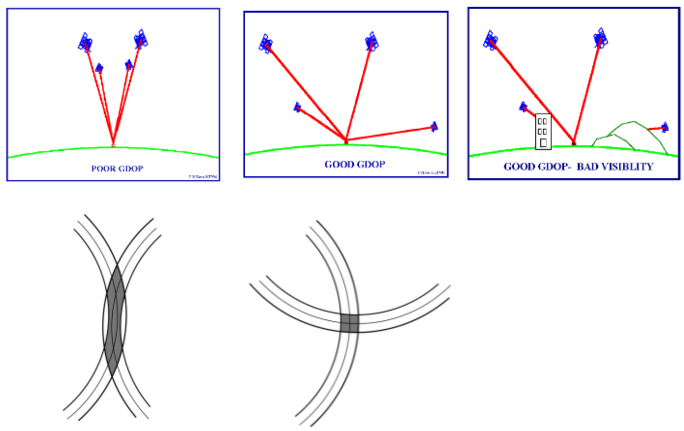
Troposphere small error, can be mitigated by local augmentation systems

Multipath – reflected path is longer than actual path

Receiver noise – causes errors in the precision of the measurement taken

Interference – local external thing is effecting quality or availability of GPS signals

GEOMETRY (DOP)



High Dilution of Precision = bad geometry = big error.

Be aware of blocking.

CLOCK ERRORS

1μs = 300m

Satellite clock errors:

- Correction by control segment
- Internet (e.g. IGS)
- Differential GPS

Receiver clock error:

- Estimate
- Differential GPS

Remember that clock errors can cause big position errors.

Satellite clock errors are compensated for by:
- Control segment (correction);
- Internet: IGS = International GNSS Service;
- Differential GPS = local beacons.

Receiver clock errors are compensated for by:
- Estimate = calculate position and timing from 4 satellites;
- See above.

MULTIPATH REFLECTION

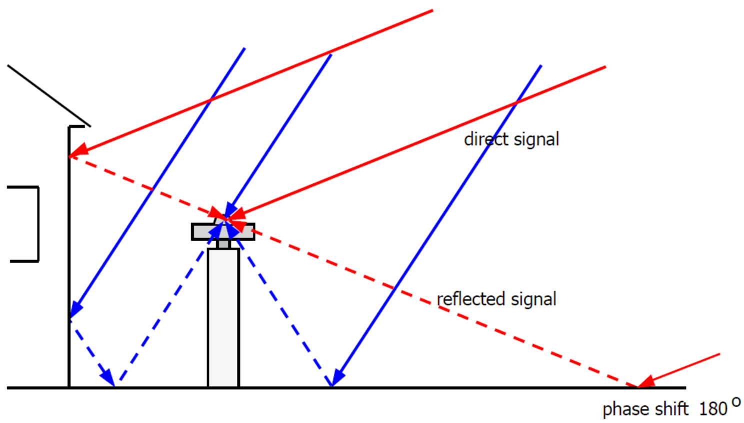


Figure: H. van der Marel

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Particularly an issue by low elevations.

TROPOSPHERE

2 components:

- Dry
- Wet

Correction by modelling and DGPS

Troposfeer: lower 10 km of the atmosphere. Tropospheric delay is used to measure the amount of moist in the atmosphere (KNMI/Siebren de Haan).

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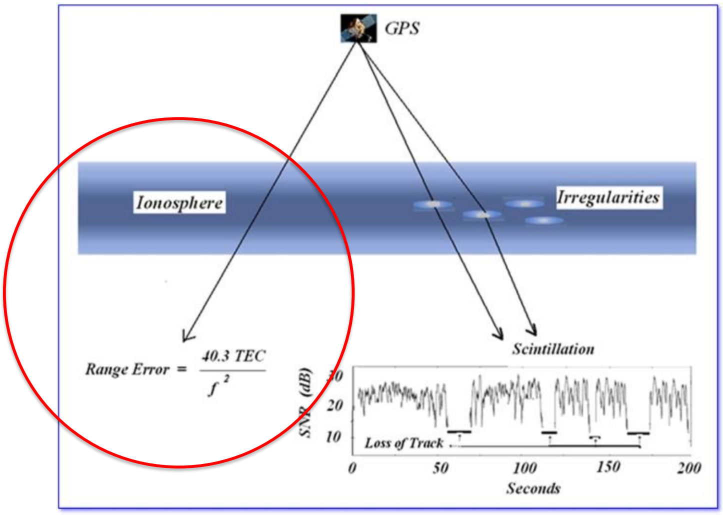
IONOSPHERE



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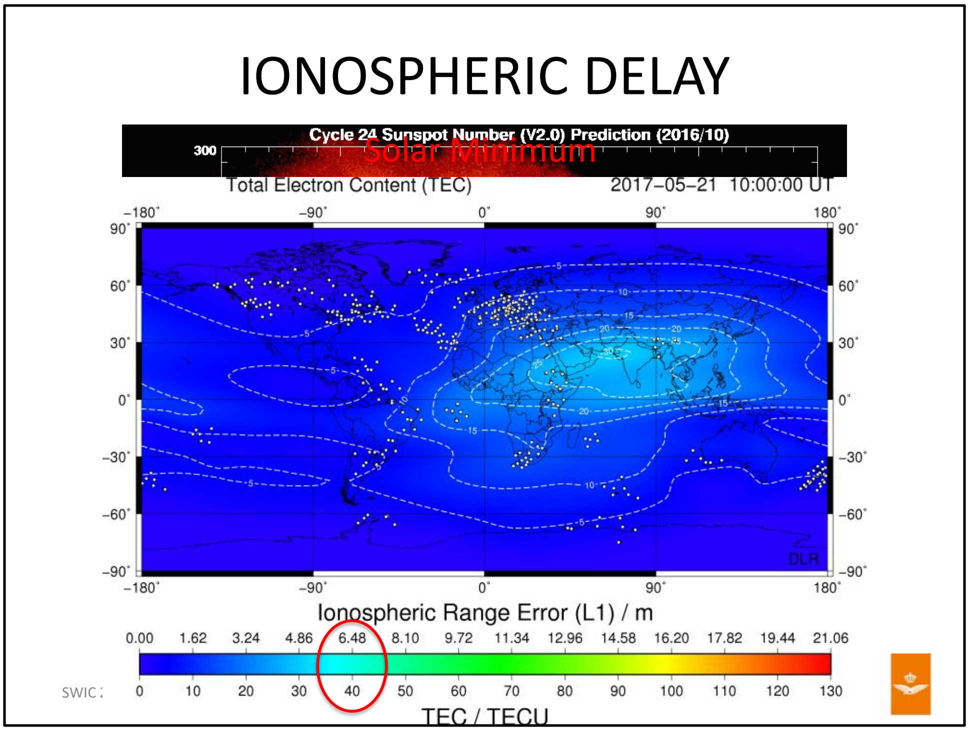
The homogeneous ionosphere causes refraction and delay, the heterogeneous ionosohere scintillation.



TEC: delay. 1 TECU ^ ~15cm.

Dependent on solar activity, season and time of day.

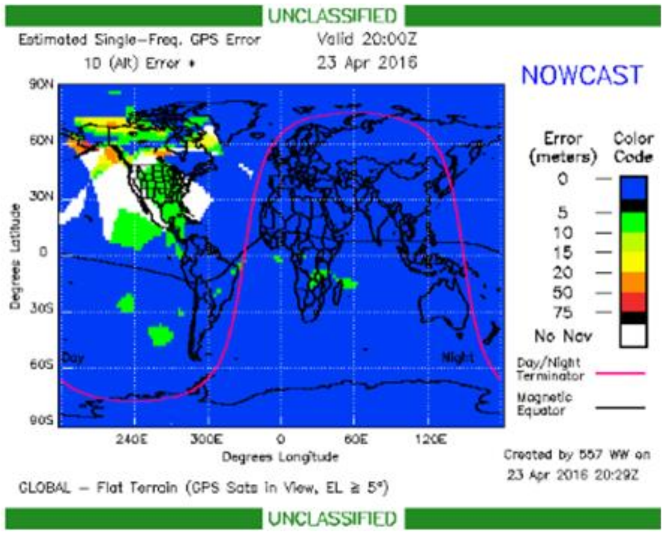
Delay is frequency dependent: dual frequency allows one to calculate the delay.

Dual frequency receivers are expensive. Single frequency receivers use the Klobuchar model to calculate the delay. However, this leaves a residual error as the ionosphere is constantly changing and never exactly its climatological average.

Other GNSS use other correction models (Galileo: NeQuick). These models correct for about 50% of the iono error.

A third way to compensate for the ionospheric delay is to use differential technique: DGPS, SBAS (WAAS, EGNOS), GBAS, RTK, etc.

MODELING RESIDUAL DELAY



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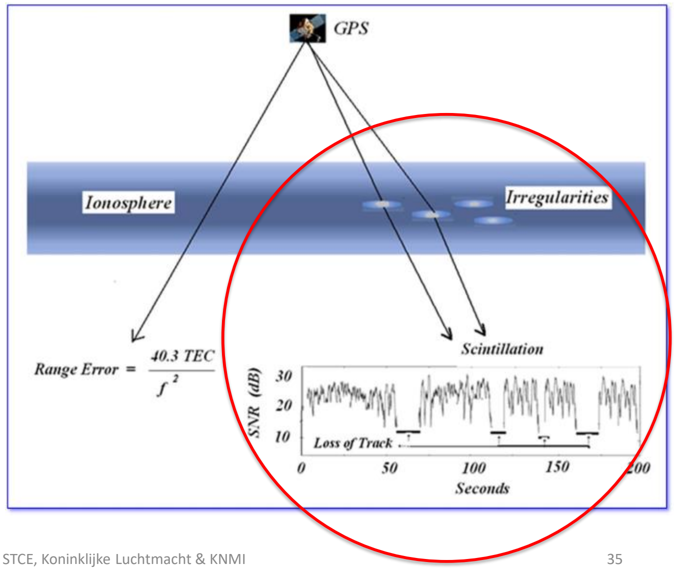
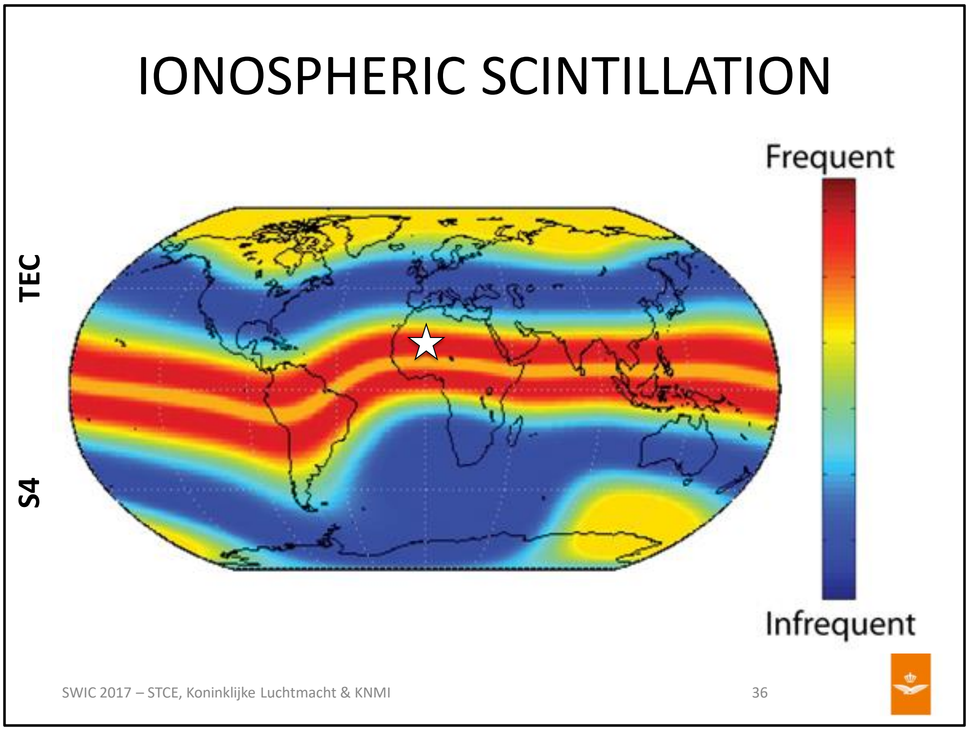
Estimated Single Frequency Error of GPS: difference between actual (IGS) en climatological (Klobuchar) ionosphere.

The picture shows the case of 23APR16/2100Z. A minor geomagnetic storm was active at that time. Kp=5.

IONOSPHERE



GPS
Ionosphere
Irregularities
Range Error = 40.3 TEC / f 2
Scintillation
SNR (dB)
30
20
10
Loss of Track
0
50
100
150
200
Seconds



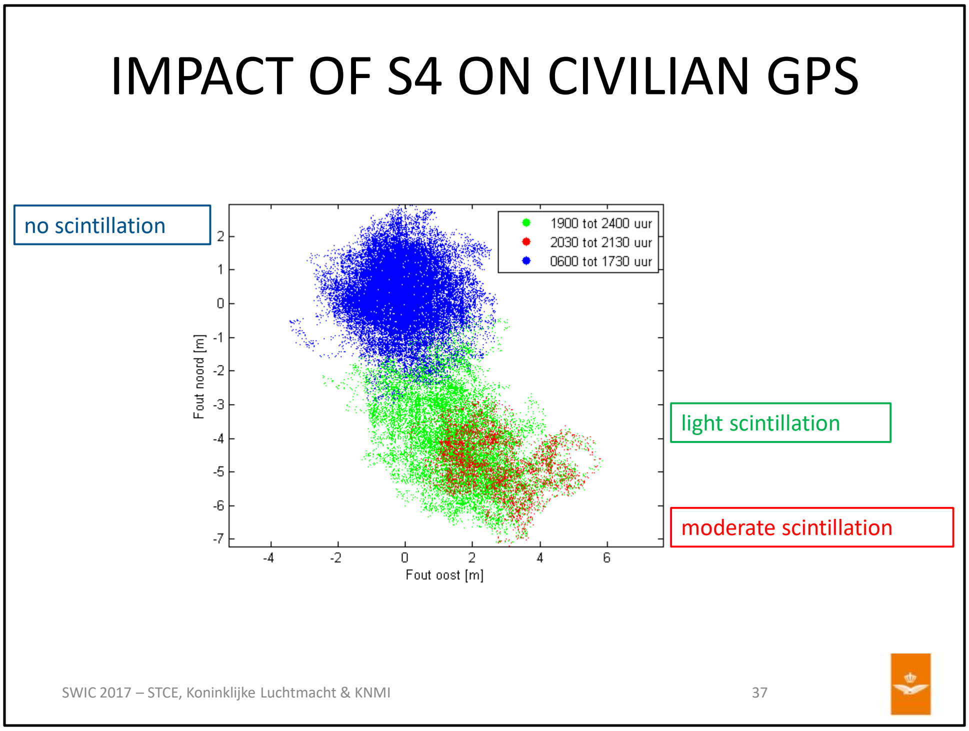
Ionospheric irregularities we find primarily at the equator and the polar region.

At the polar region it is associated with (sub)storms/aurora, at the equatorial region with the Appleton anomaly.

At the Appleton or equatorial anomaly it is a daily phenomenon with a diurnal, seasonal and solar variation.

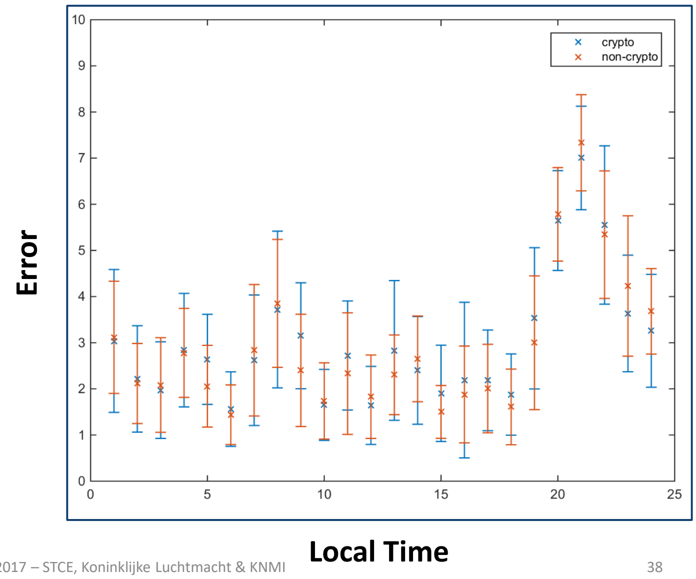
Scintillation is expressed in S4 (amplitude variations of the carrier wave) or Phi60 (phase variations of the carrier wave).

Only limited mitigations possible. Best approach: exclude scintillating satellites.



Typical error on a civil GPS receiver during an evening in Mali. When scintillation is most, the error is biggest (red).

ERROR BY S4 IN COURSE OF DAY



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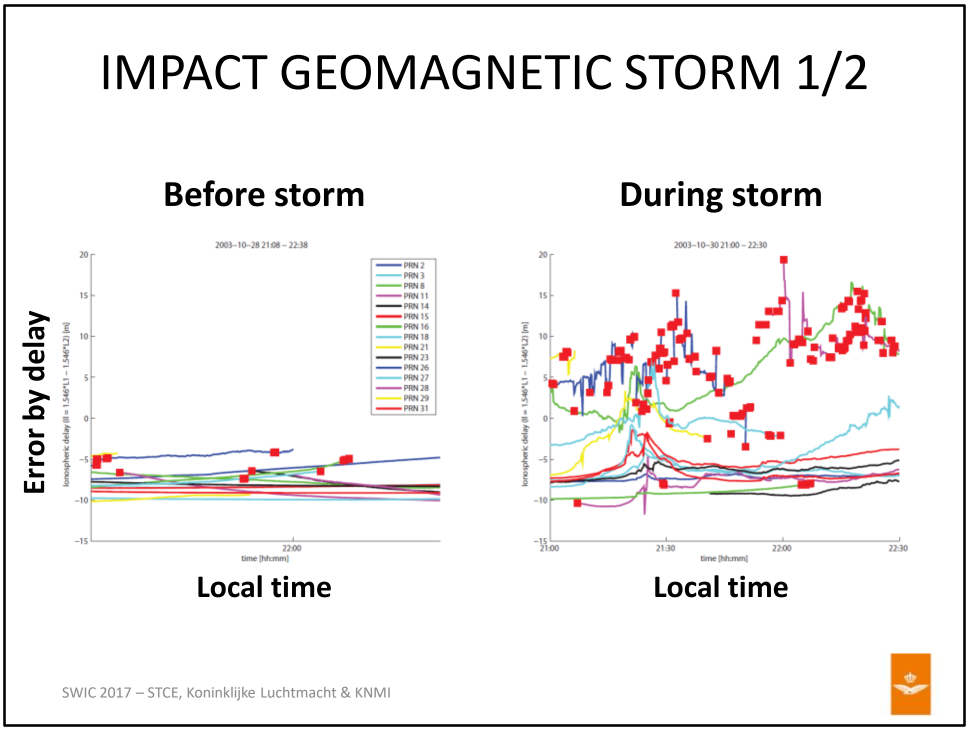
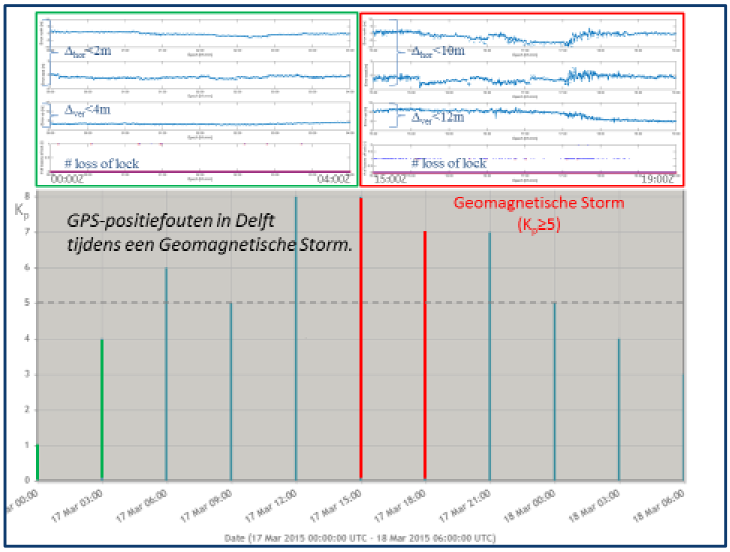
Same measurement, now in time and for a military receiver without crypto turned on (so, working as a single frequency civil receiver).



During geomagnetic storms ionospheric irregularities move equatorward. These pictures show the position errors of several satellites before the Halloween storm of 30OCT2003 and during this storm.

IMPACT GEOMAGNETIC STORM 2/2



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The same happend during the storm of 17MAR15 in Delft (Netherlands). At the upper left picture you find the error and losses of lock before the storm and at the upper right during the storm. Both the position error as well as the losses of lock increase significantly during the storm.

SOLAR RADIO BURST

- Interference by the Sun
- Requires:
  - right frequency;
  - right polarization;
  - right intensity.
- Cases:
  - 6 December 2006
  - 24 September 2011
  - 4 November 2015

Also see slide 44 – 49 of the presentation about the ionosphere by Nicolas Bergeot.

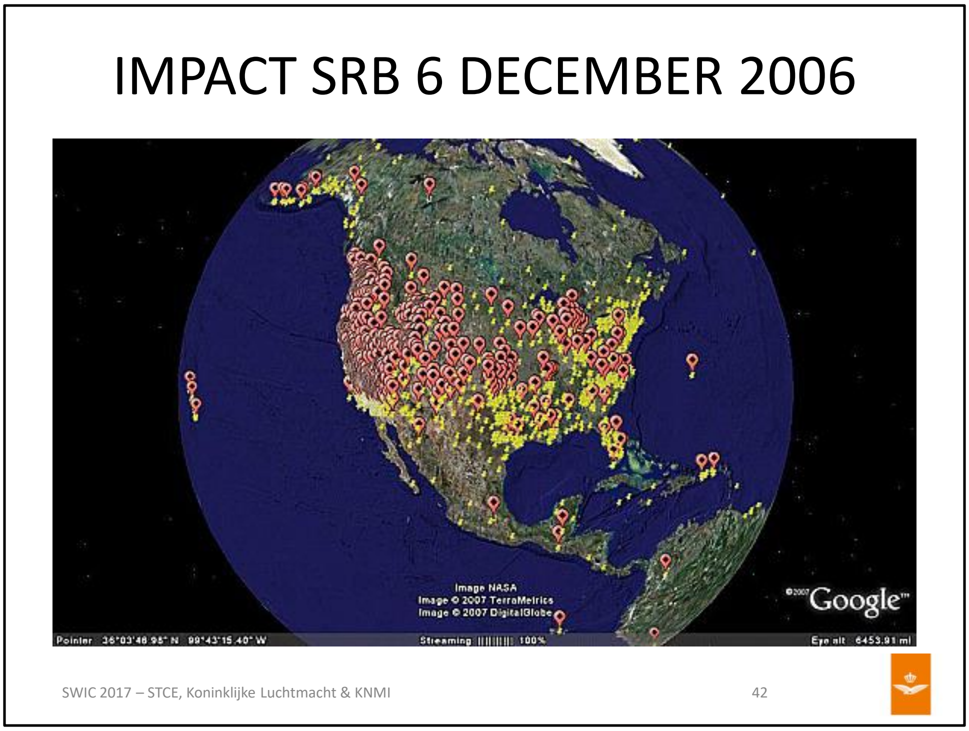

Illustration of the number of receivers severely impacted by the SRB. The yellow markers indicate all currently available geodetic quality receivers available through the World Wide Web, including those from the GPS receivers from the IGS and CORS networks. The red markers indicate all of the receivers that were severely impacted during the peak of the solar radio burst from 1930–1940 UT.

Q: How big is 1 SFU? A: 10^-22 W / m / Hz.

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http://onlinelibrary.wiley.com/doi/10.1029/2007SW000375/full

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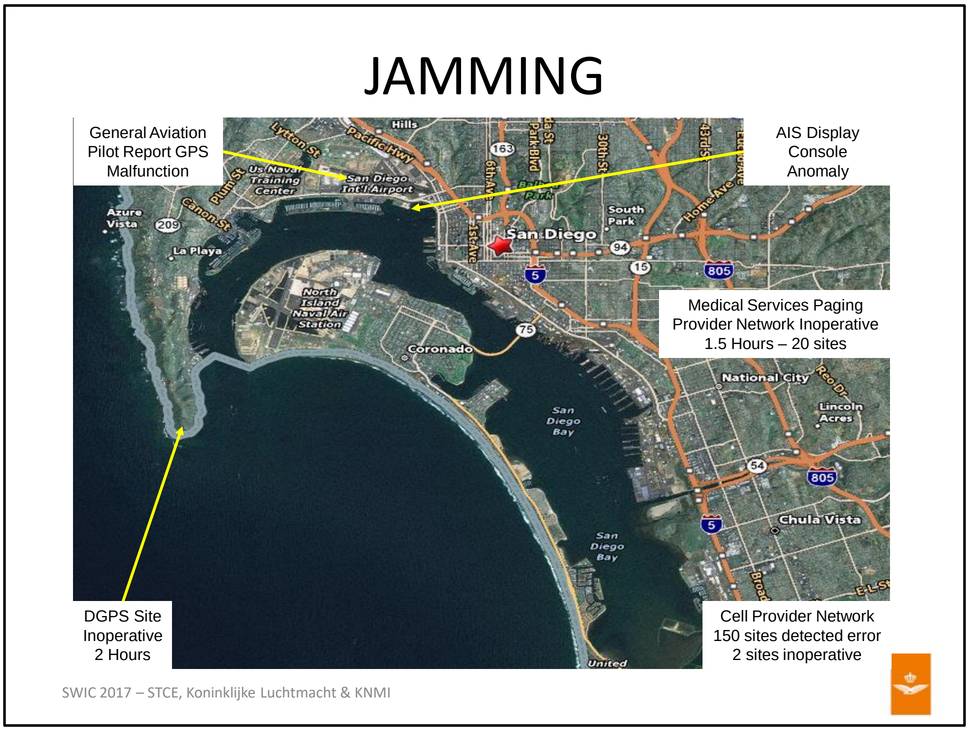


Jamming: deliberately interfering with wireless connections.

Two US Navy ships participated in a communications jamming exercise off the coast of San Diego. It took the affected users of GPS three days to find the cause.

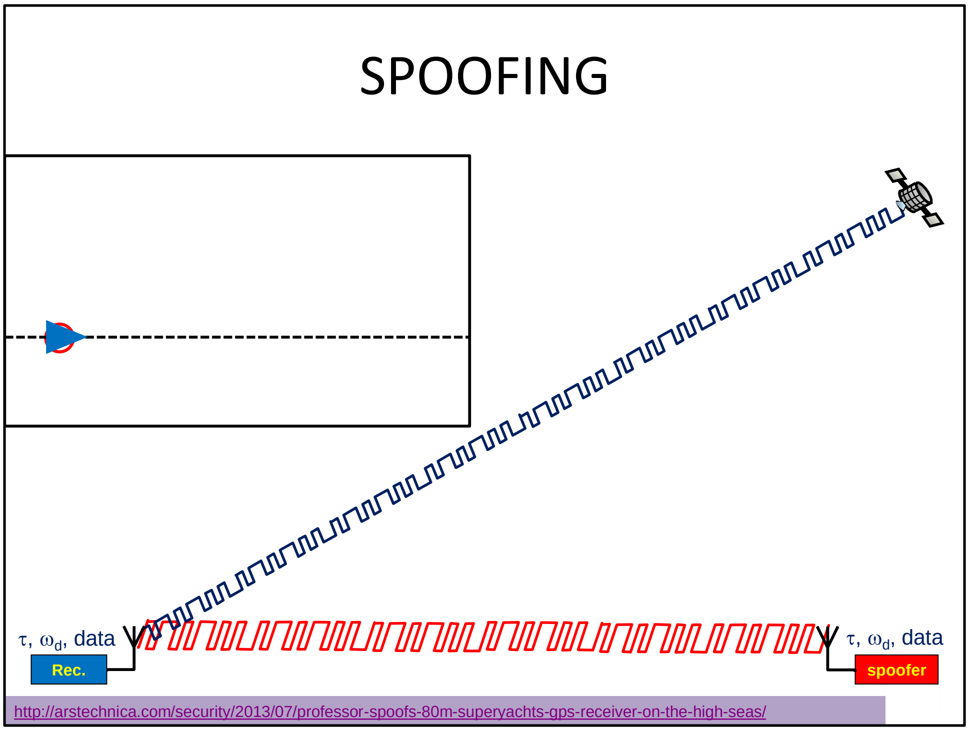
If GPS is jammed (either on board of a ship or aircraft or on the ground), think of the avalanche of effects that starts (e.g. many computers need accurate timing to participate in networks, but also INS-drift).

https://en.wikipedia.org/wiki/Radio_jamming

NORTH KOREAN JAMMERS

Dates	Aug 23–26, 2010 (4 days)	Mar 4–14, 2011 (11 days)	Apr 28 – May 13, 2012 (16 days)
Jammer locations	Kaesong	Kaesong, Mountain Kumgang	Kaesong
Affected areas	Gimpo, Paju, etc.	Gimpo, Paju, Gangwon, etc.	Gimpo, Paju, etc.
GPS disruptions	181 cell towers, 15 airplanes, 1 battle ship	145 cell towers, 106 airplanes, 10 ships	1016 airplanes, 254 ships

Kim Jong-un likes jammers too.



The idea behind spoofing is to take over control unnoticed. The signal of the GPS-satellites is mimicked only a little stronger than the original signal. The it is altered a bit. The boat ***thinks*** it is off track. Once this is noticed, the boat steers to 'correct', thereby really getting off track.

https://en.wikipedia.org/wiki/Spoofing_attack
https://arstechnica.com/security/2013/07/professor-spoofs-80m-superyachts-gps-receiver-on-the-high-seas/

SPOOFING: DEN HELDER OR …

Few hundreds of dollars to build your own spoofer.

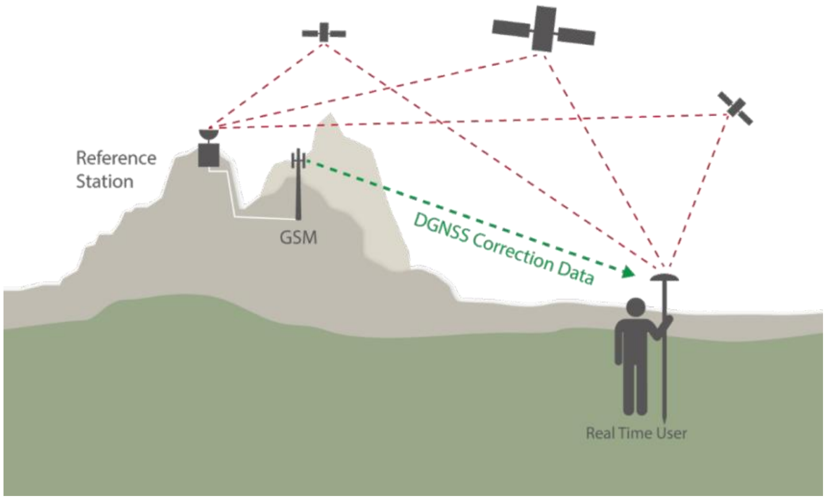
Keep in mind there are many error sources and cheap ways of misleading GPS-receivers that have nothing to do with SPWX.

SUMMARY

- GPS
  - Positioning, Navigation & Timing
  - Space, ground & user segments
  - Many error sources

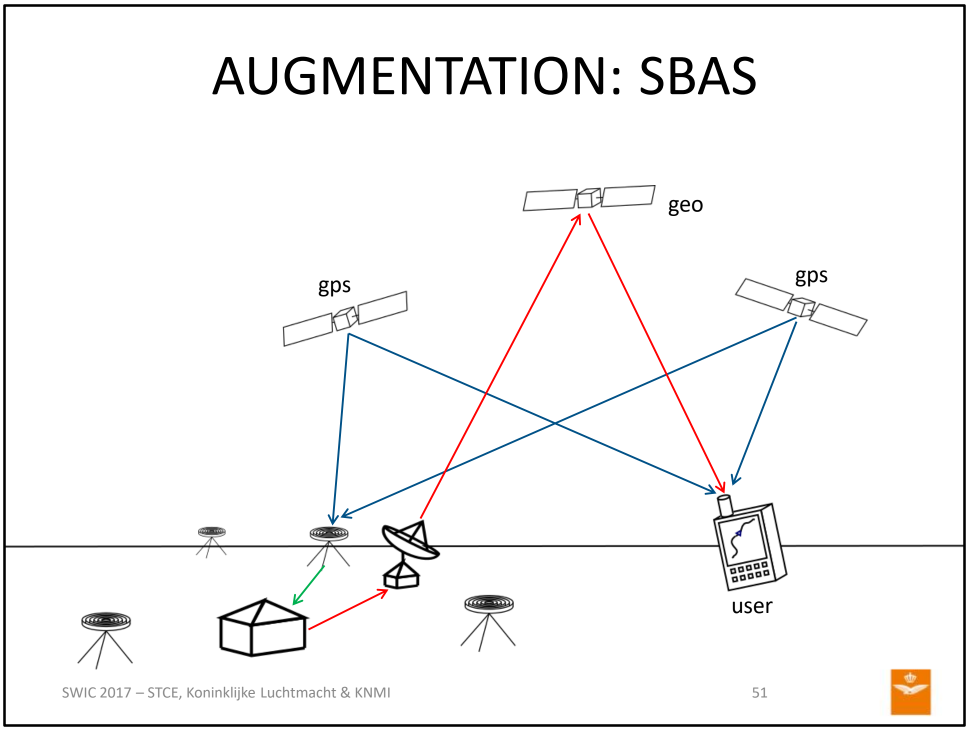
- SPWX IMPACTS
  - Ionospheric delay
  - Ionospheric scintillation
  - Interference by solar radio bursts

AUGMENTATION: DGPS



DGPS: Referentie stations berekenen fouten en sturen correctie door aan gebruikers.

Hierbij heb je voor de correctiefactoren een aparte ontvanger nodig.



Meten op de grond, correctie bepalen in CS, uploaden naar geo satelliet, die downloadt 'm op L1 met een eigen PRN, die wordt weer ontvangen door GPS.

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OTHER GNSS

- Galileo
- GLONASS
- BeiDou

https://en.wikipedia.org/wiki/Galileo_(satellite_navigation)
https://en.wikipedia.org/wiki/GLONASS
https://en.wikipedia.org/wiki/BeiDou_Navigation_Satellite_System