GNSS Reflectometry (GNSS-R)

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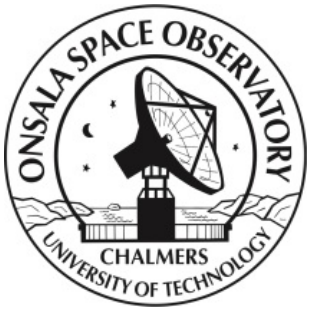
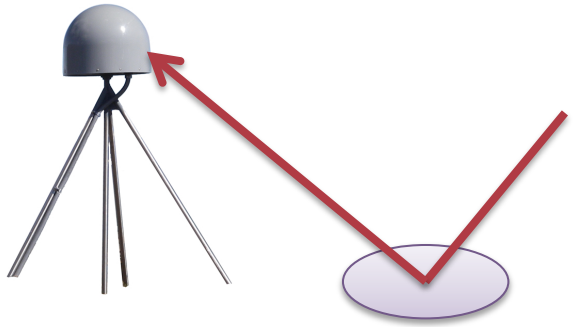
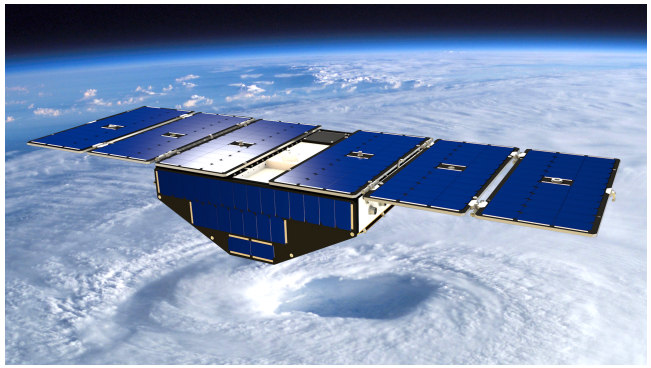


HERE'S WHAT YOU'LL LEARN

- Ground-based GNSS-R
  - Measurement principle(s)
  - Applications & results
- Air- and spaceborne GNSS-R
  - Measurement principle
  - Applications
  - Upcoming missions



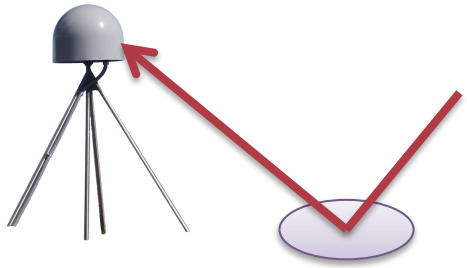


Ground-based GNSS-R

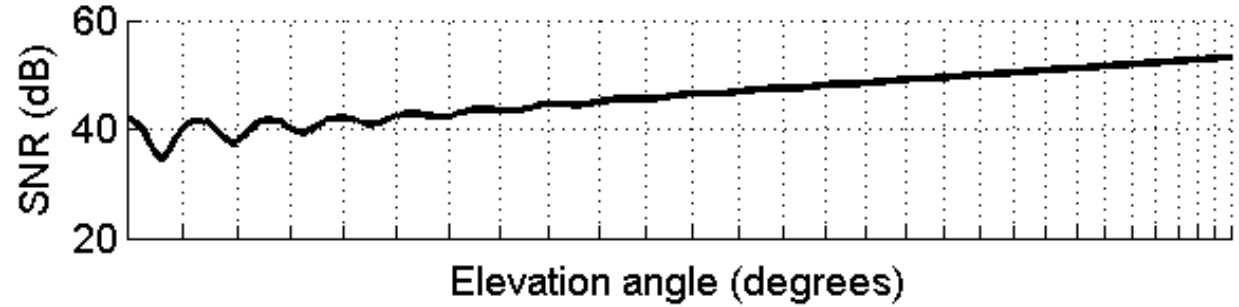
- Not only “direct” GNSS signals, but also reflected signals (“multi-path”) enter the antenna
  - Avoid by all means for PNT applications
  - BUT: contains valuable
    - Geometric and
    - Radiometric

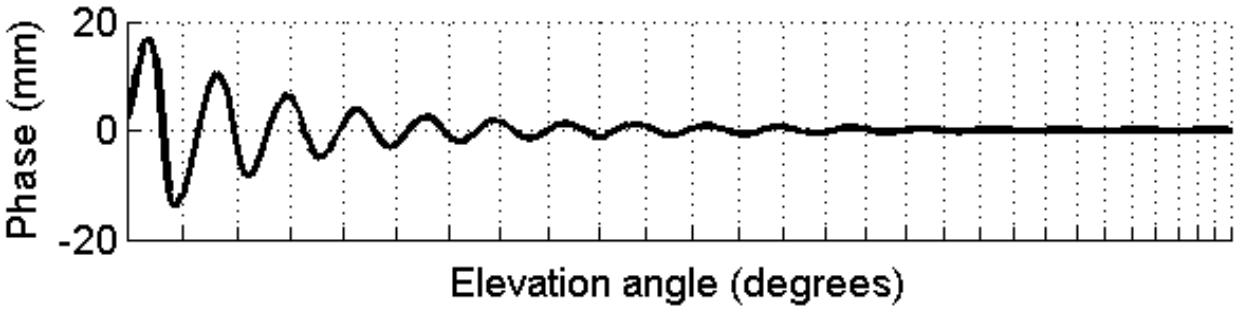
    information about the environment around the antenna

(Simulated) multi-path effects

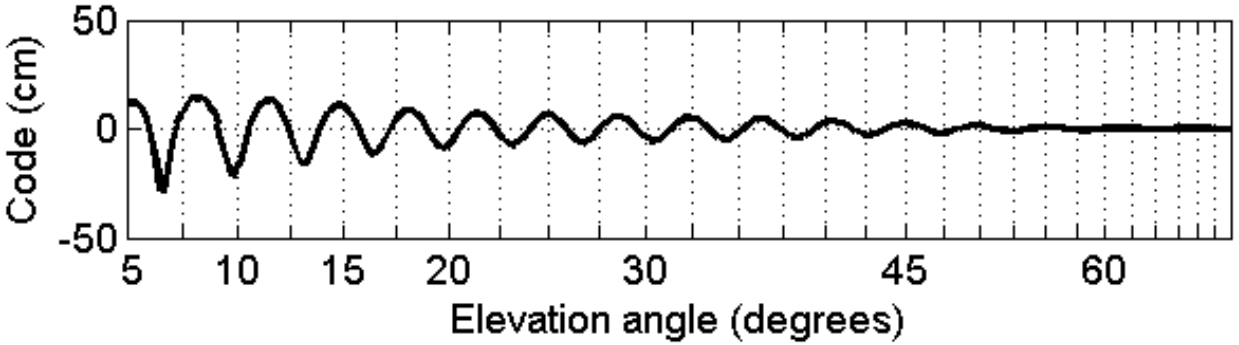


Signal-to-noise Ratio (SNR)



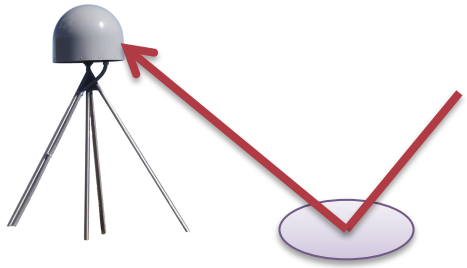


Carrier phase

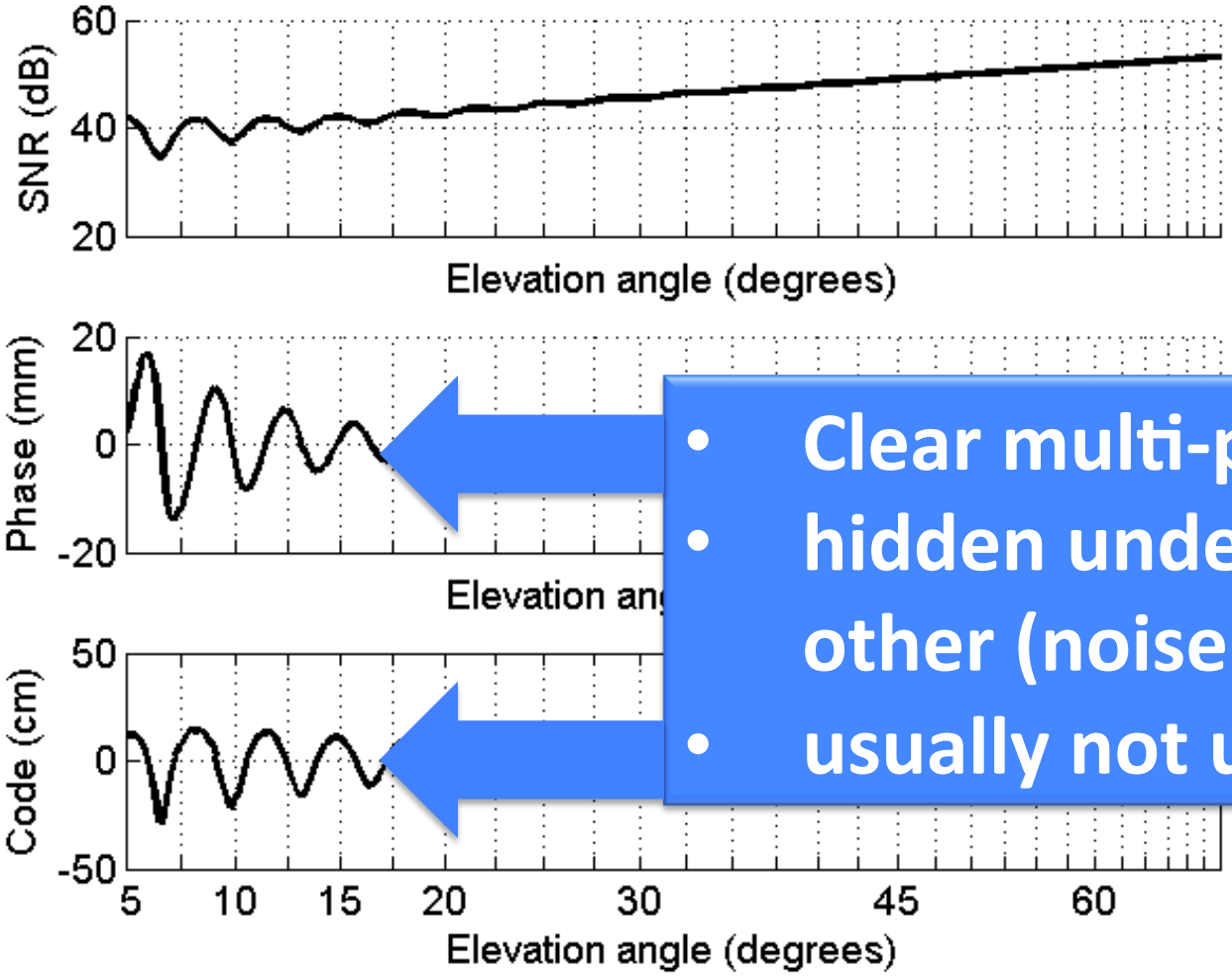


Code phase

(Simulated) multi-path effects

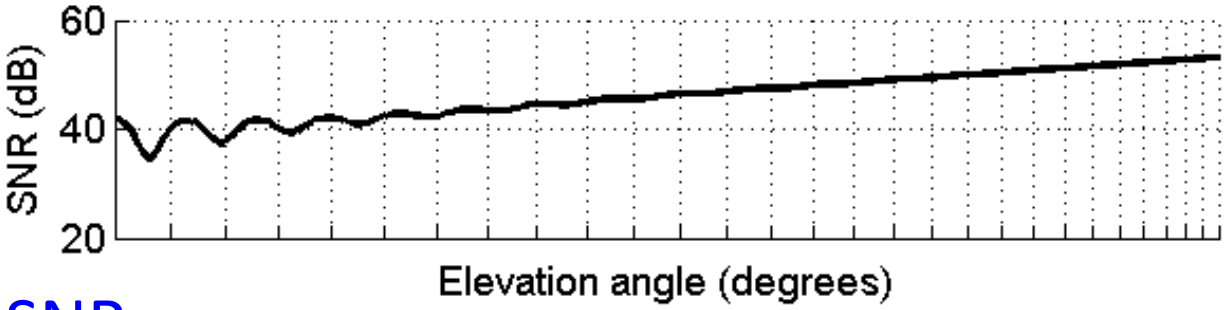


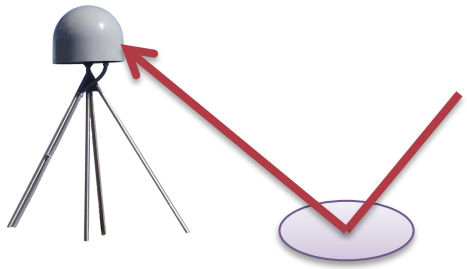
Signal-to-noise Ratio (SNR)



- **Clear multi-path signatures**
- **hidden under a lot of other (noise) contributions**
- **usually not used for GNSS-R**

(Simulated) multi-path effects

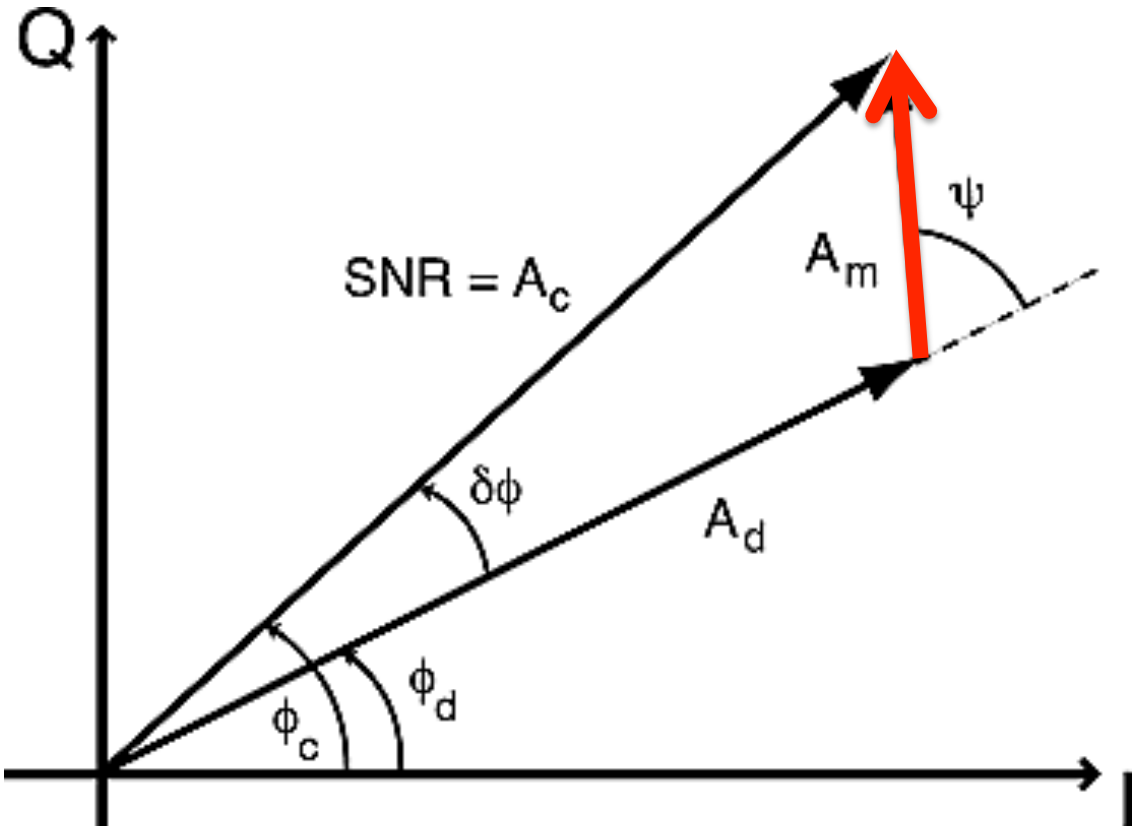




Signal-to-noise Ratio (SNR)

SNR:

- shown here in logarithmic scale (dB) -> a very clear signal in linear scale
- Multi-path signal is directly accessible (e.g. RINEX files)
- Contains information related to
  - geometric properties and
  - radiometric properties
- SNR is the usual choice for ground-based GNSS-R



$$SNR^2 \equiv A_c^2 = A_d^2 + A_m^2 + 2A_dA_m \cos\psi$$

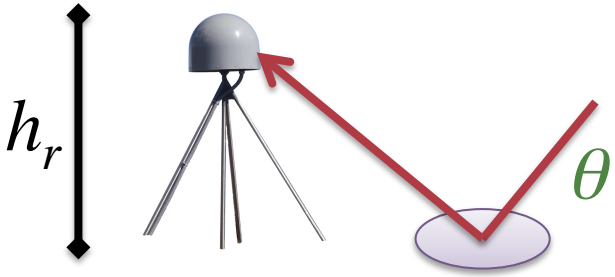
can be de-trended/modeled

contains MP information

$$SNR^2 \sim 2A_dA_m \cos\psi$$

$$\psi = \frac{2\pi}{\lambda}\delta$$

excess path due to MP

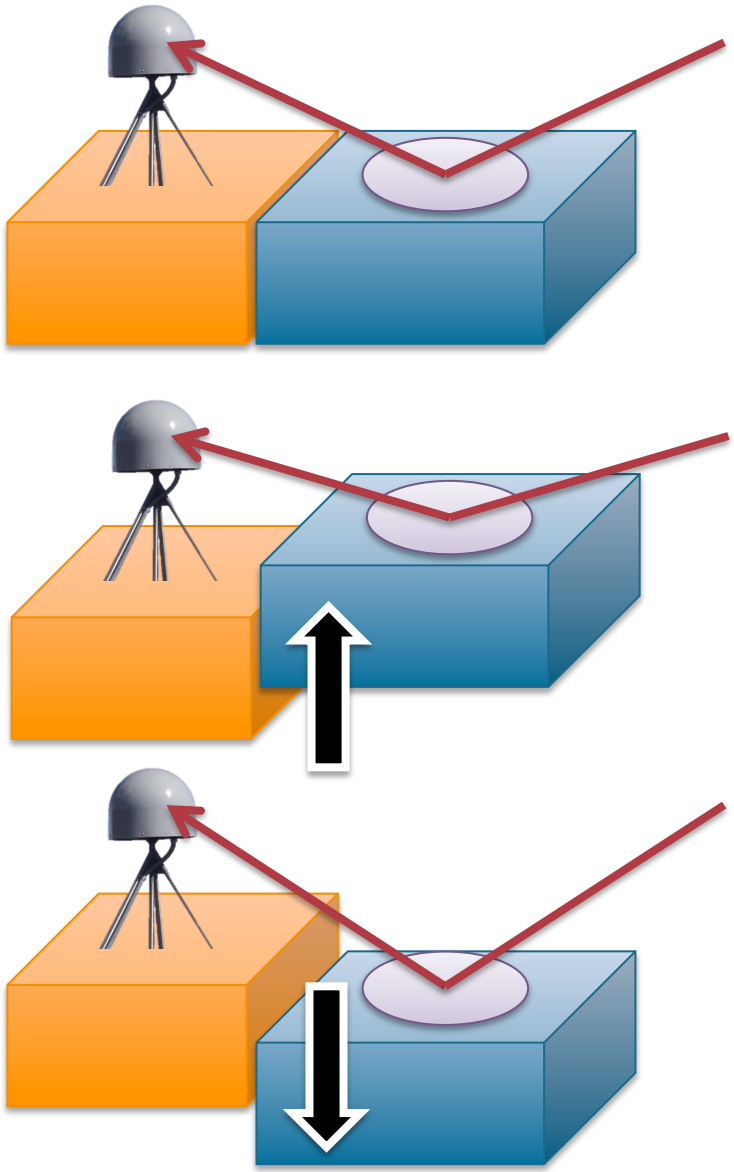


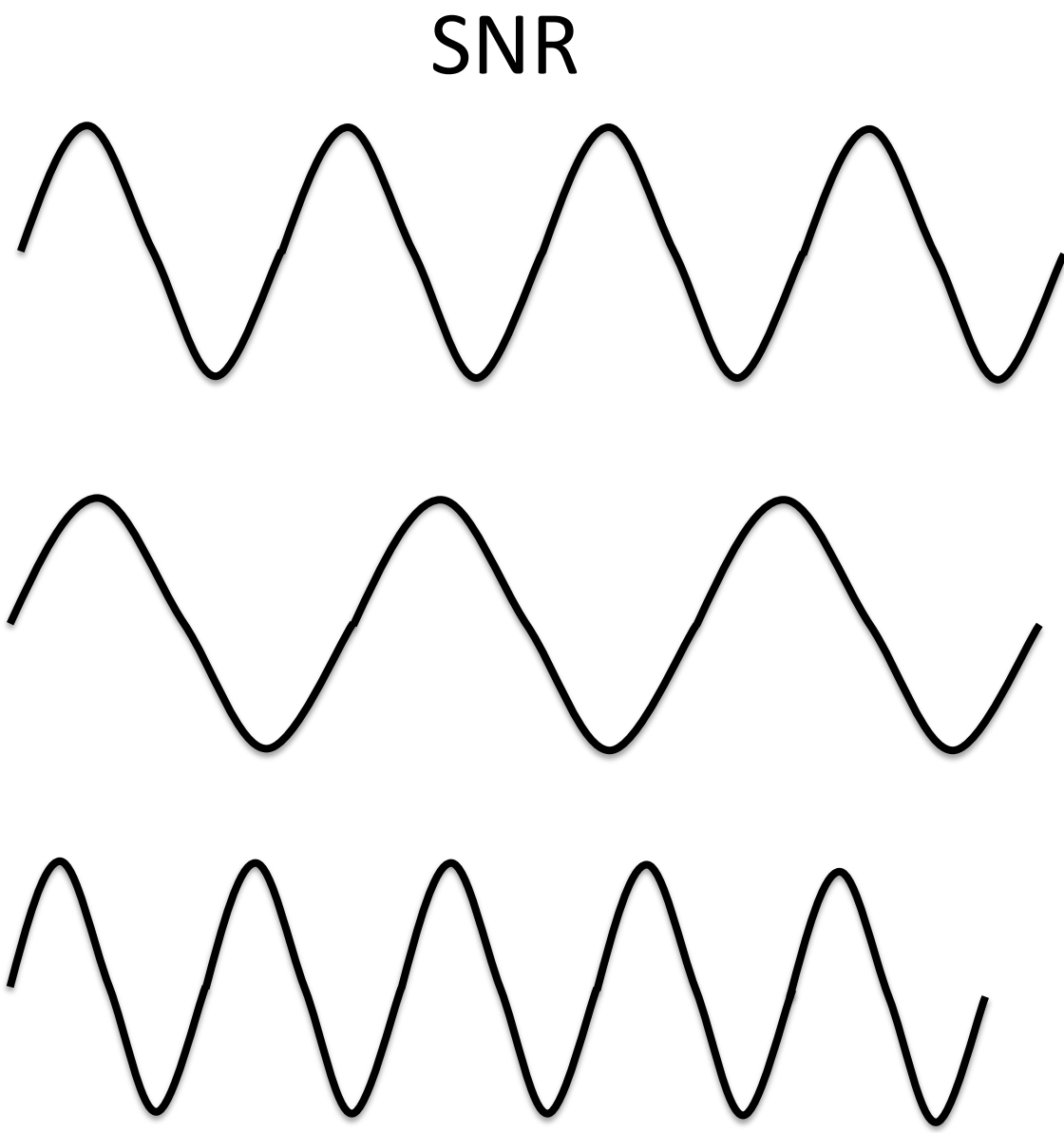
Excess path = height of the antenna above the reflector x sin (elevation)

$$\psi = \frac{4\pi h_r}{\lambda}\sin(\theta)$$

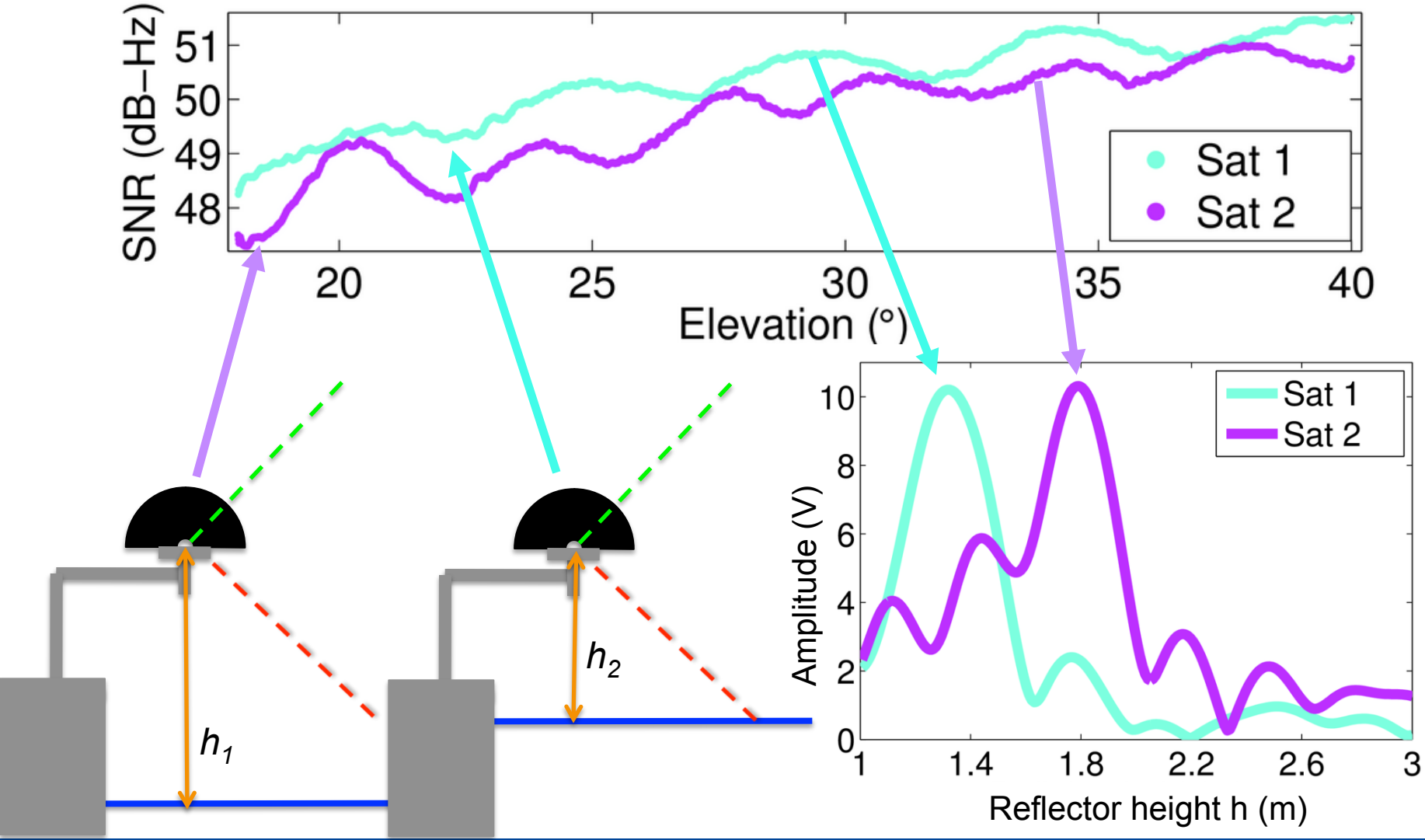
We have found a relation between SNR and the reflecting geometry!

Interpretation of the relation between reflector height and SNR



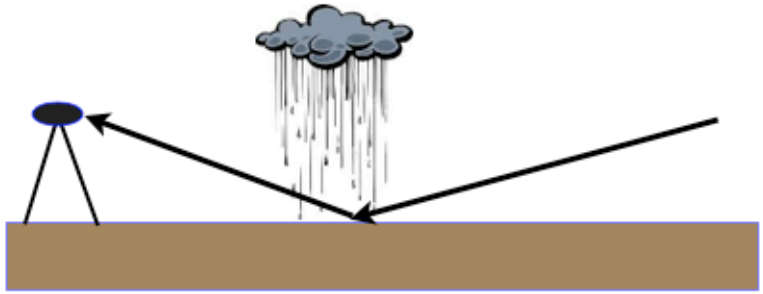

SNR

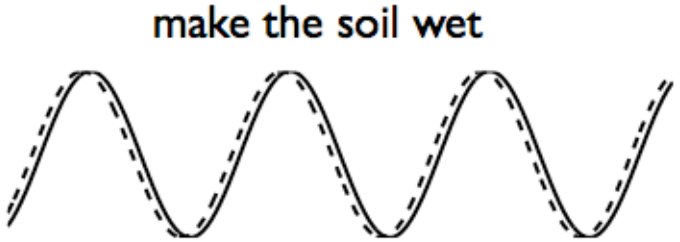
Example:
GTGU, Onsala Space Observatory, Sweden


SNR (dB–Hz)
51
50
49
48
20
25
30
35
40
Elevation (°)
Sat 1
Sat 2
h_1
h_2
Amplitude (V)
10
8
6
4
2
0
1
1.4
1.8
2.2
2.6
3
Reflector height h (m)
Sat 1
Sat 2

But there is more information hidden in SNR data !

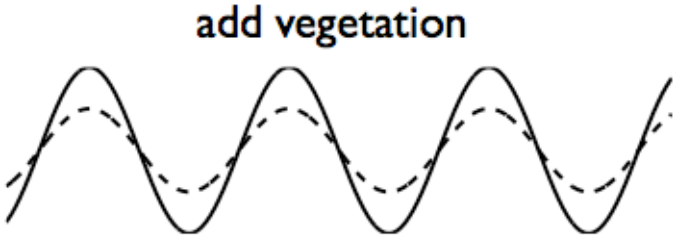
Soil moisture





Phase shift in SNR!

Vegetation



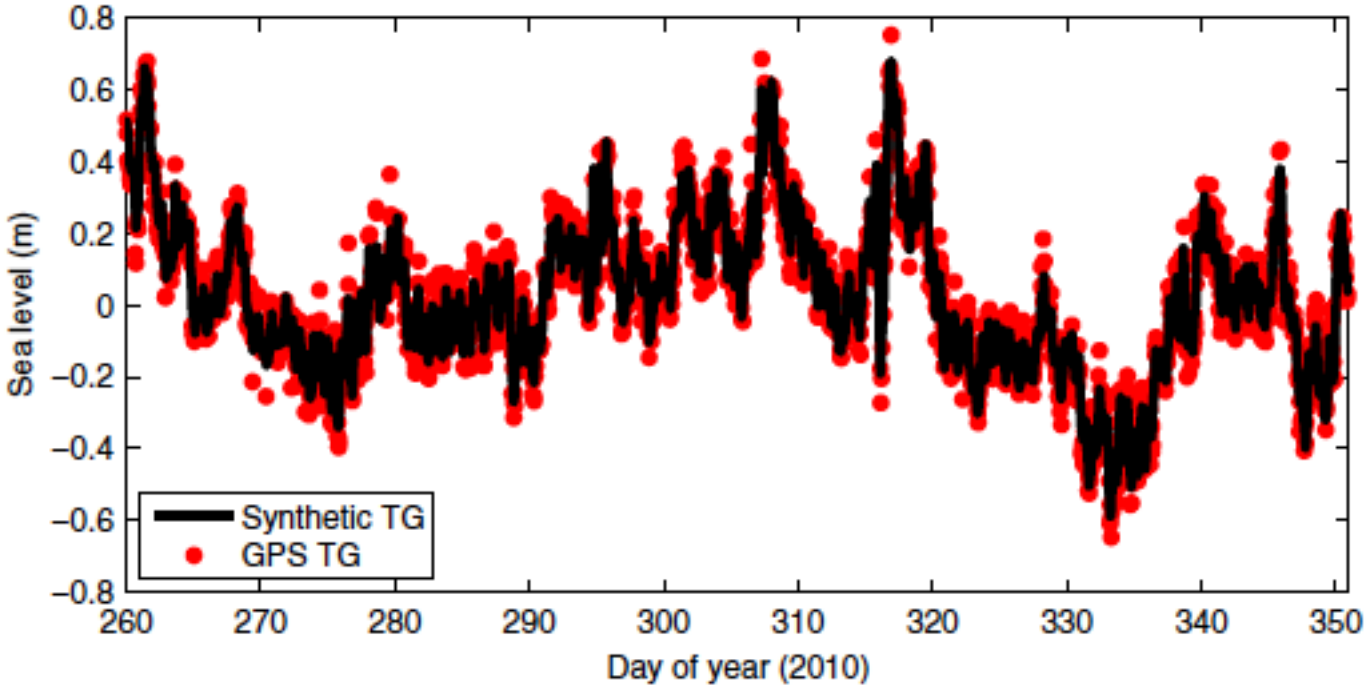
Amplitude change of SNR!

(image source: http://xenon.colorado.edu/spotlight/kb/gps_reflections/reflections_101.001.png)

Some examples

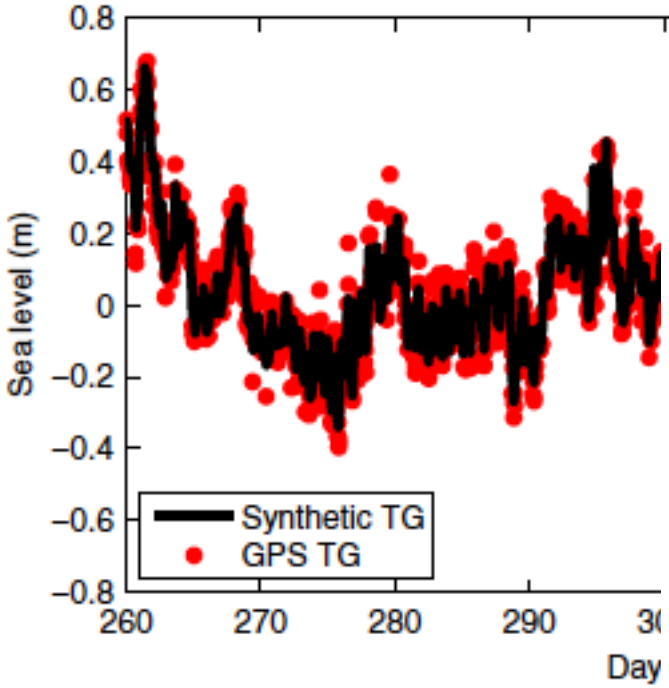
Sea-level

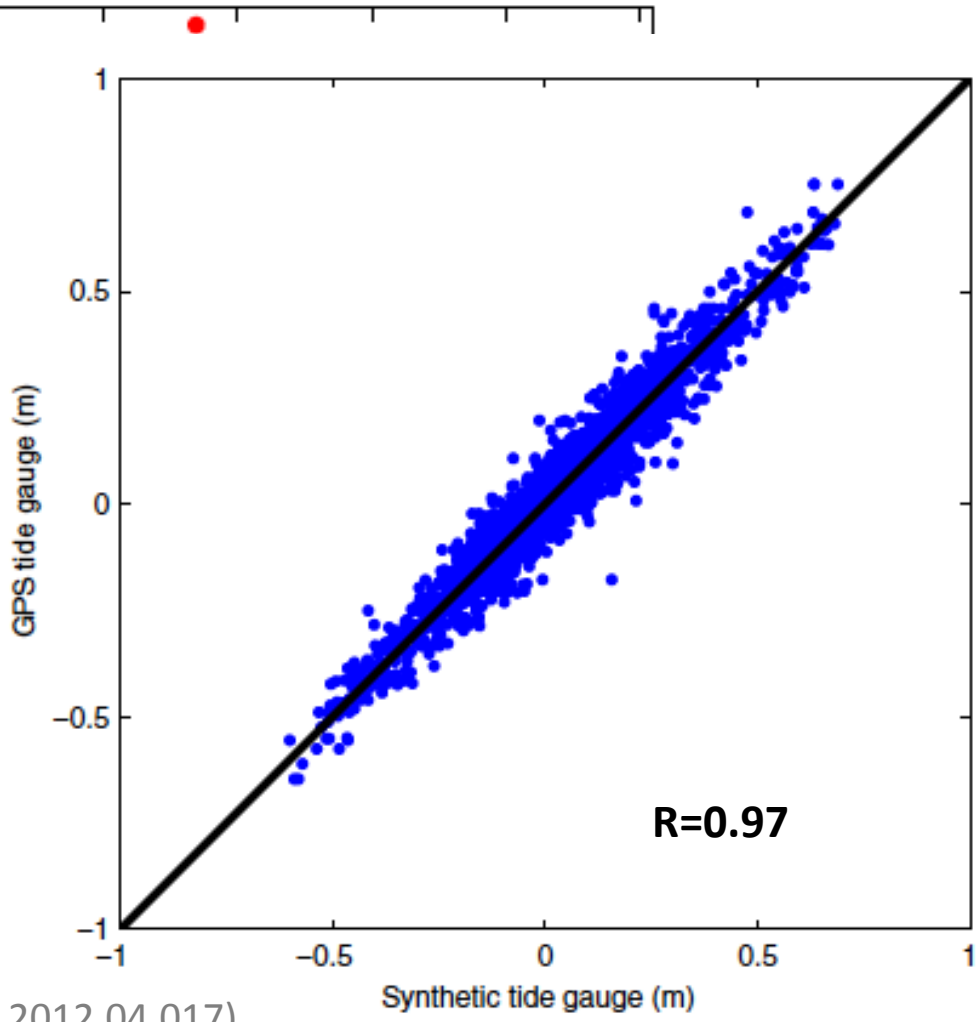
Sea-level measurements at Onsala, Sweden



(images from http://dx.doi.org/10.1016/j.asr.2012.04.017)

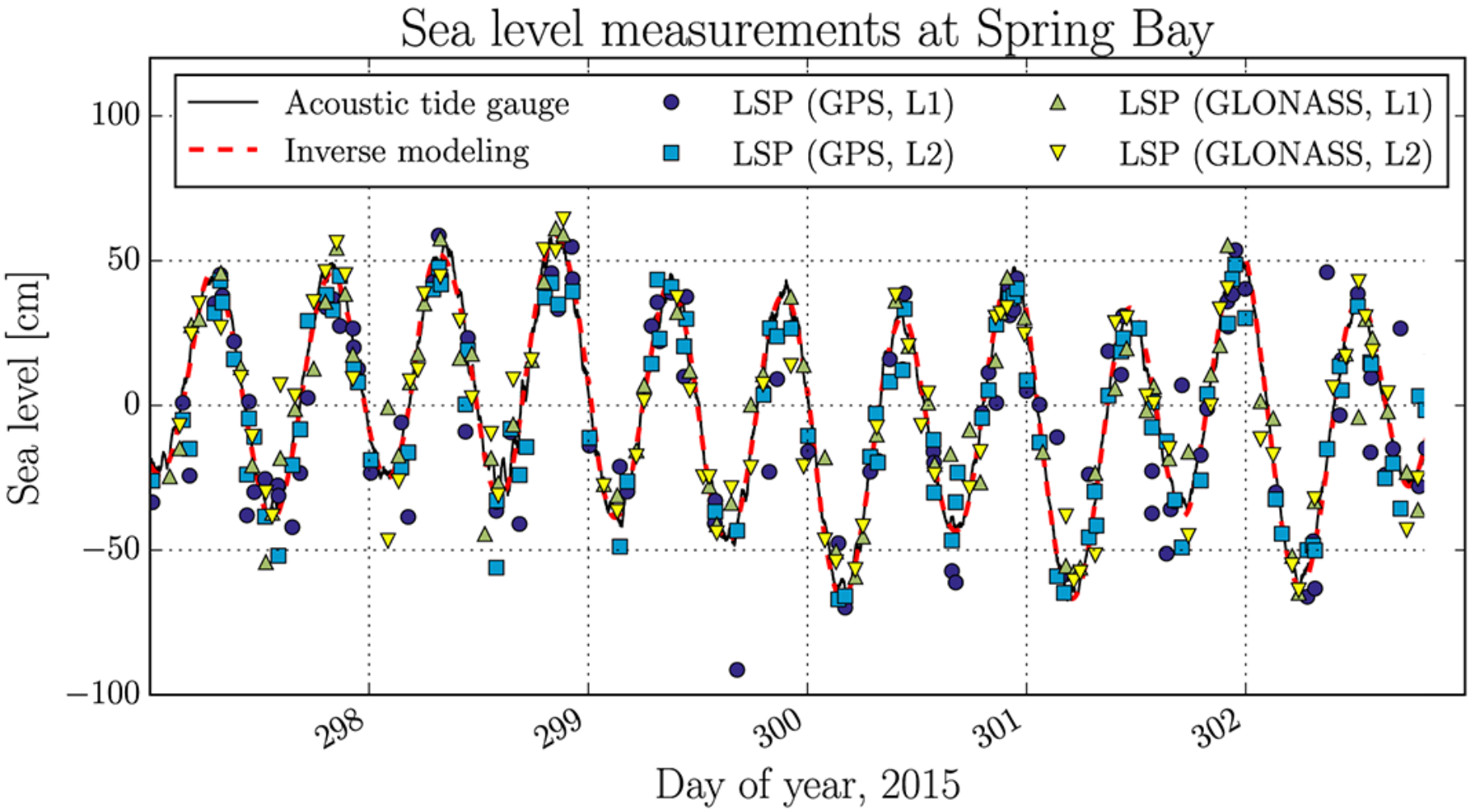
Sea-level measurements at Onsala, Sweden





(images from http://dx.doi.org/10.1016/j.asr.2012.04.017)

Better precision through inverse modeling (Strandberg et al., 2016)



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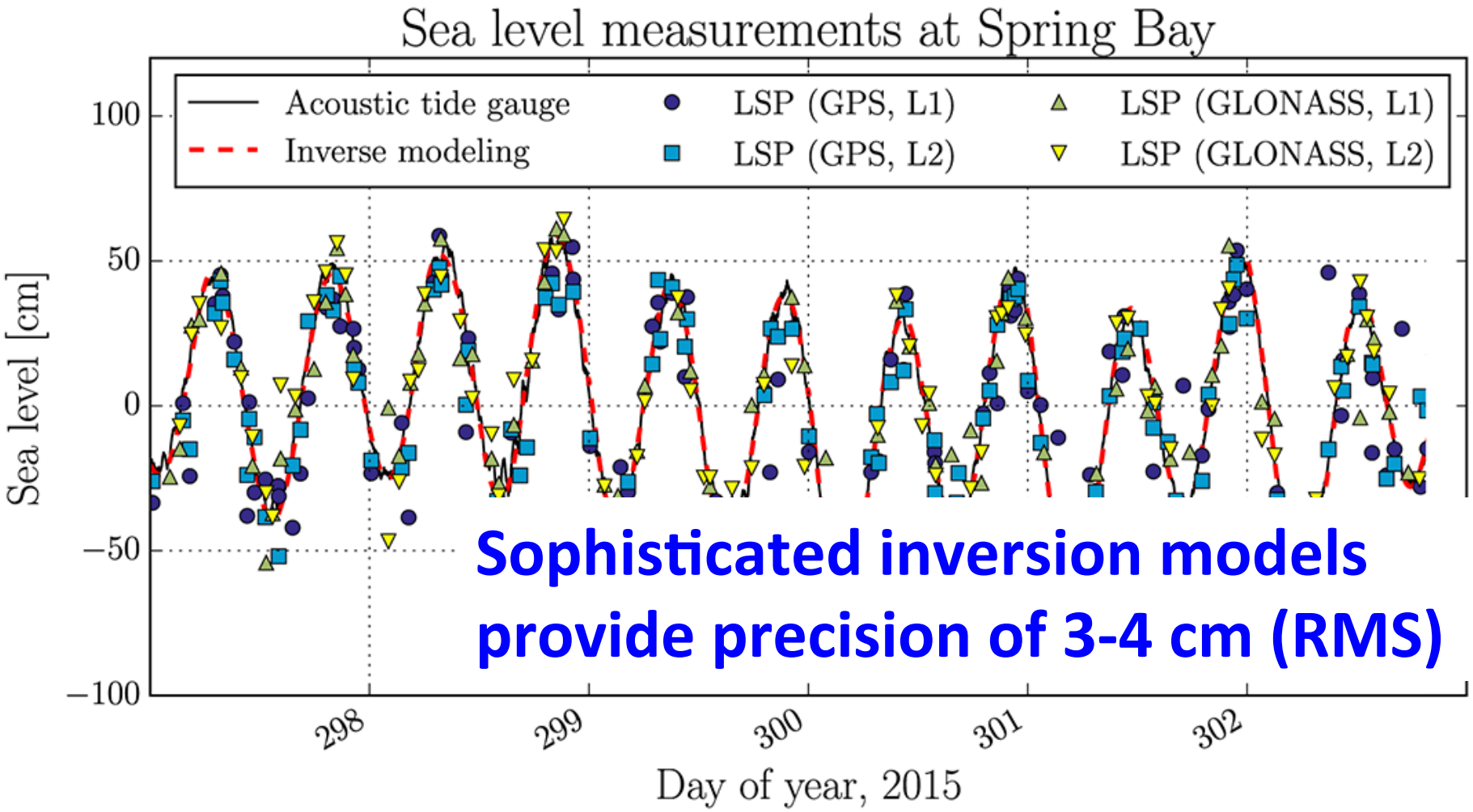
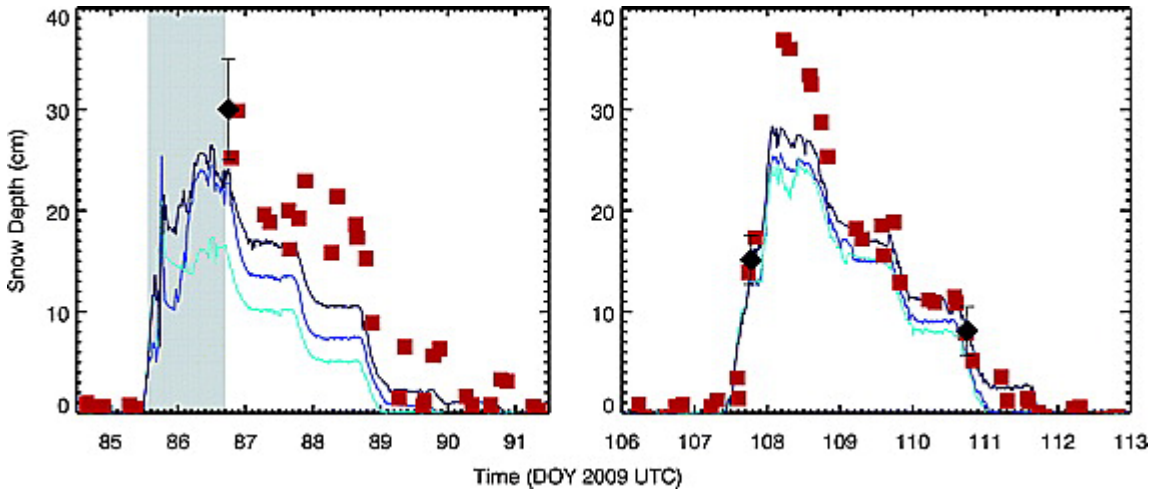


Sophisticated inversion models provide precision of 3-4 cm (RMS)

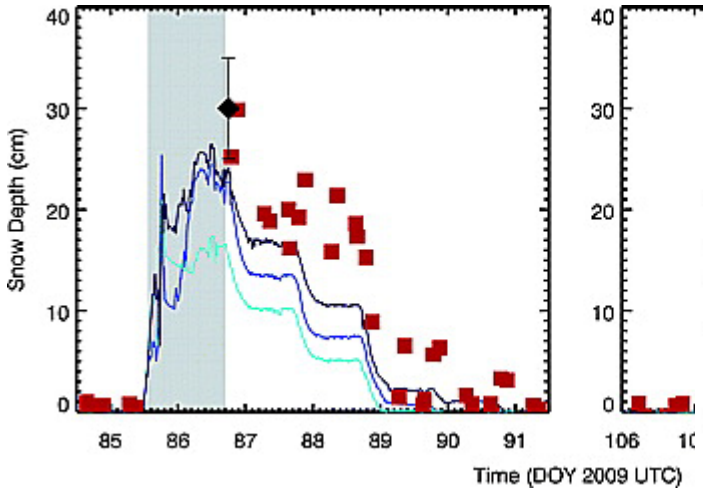
Snow height

Marshall GPS site, USA



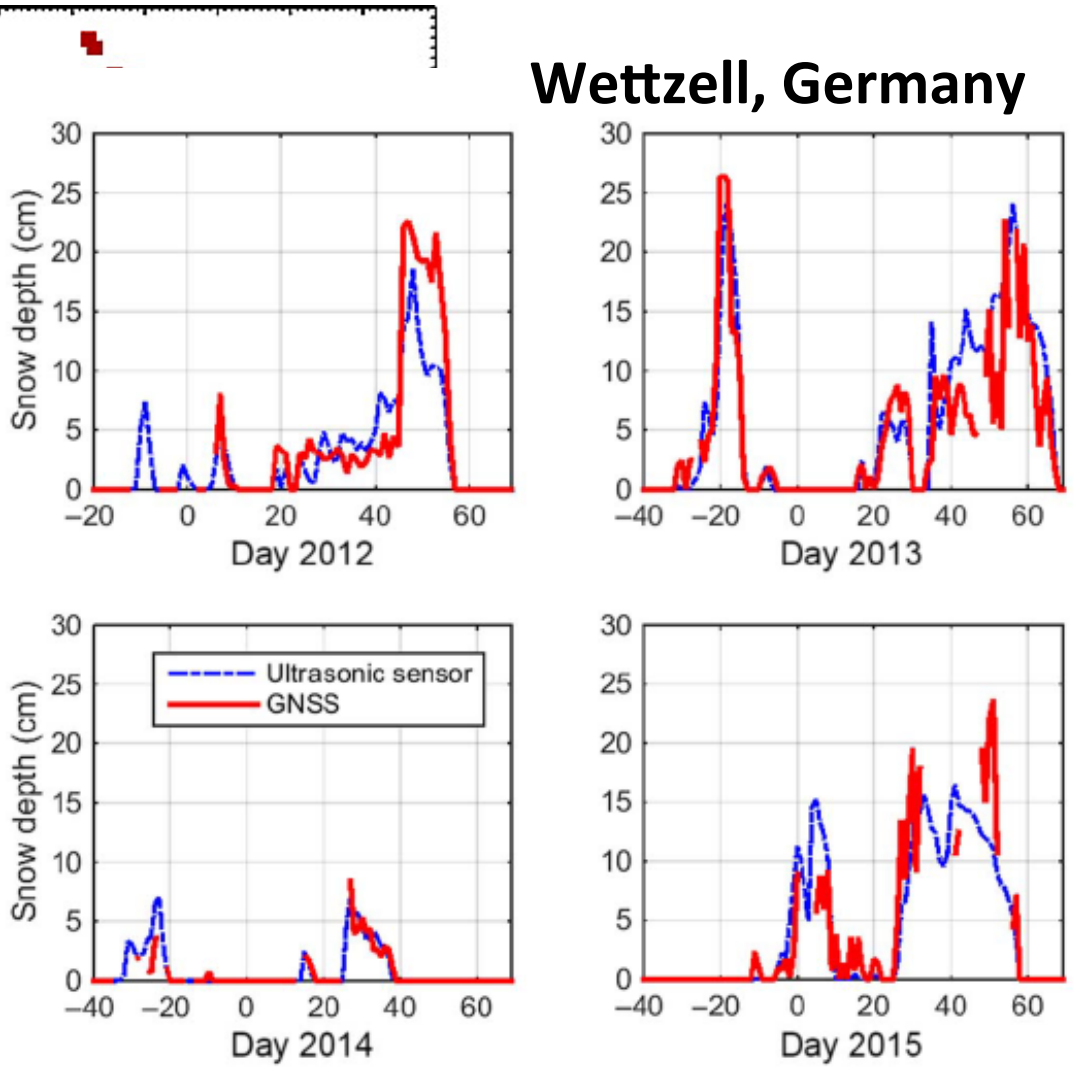
(image from doi: 10.1029/2009GL039430)

Marshall GPS site, USA



(image from doi: 10.1029/2009GL0394

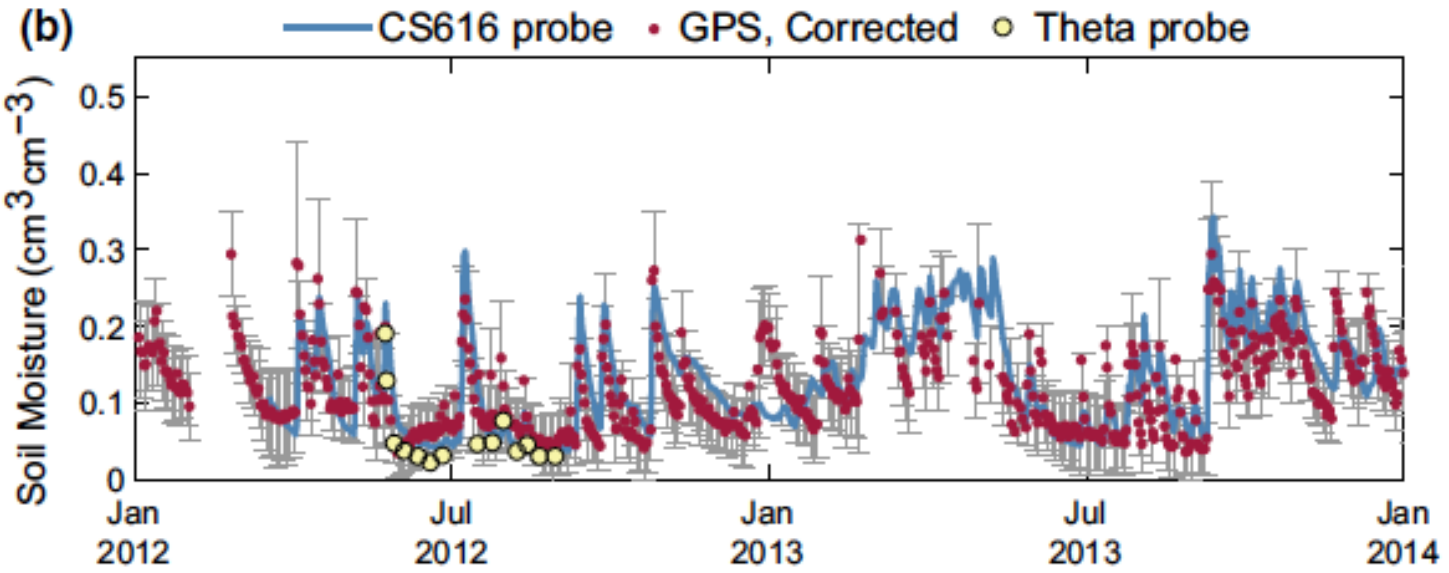
Wettzell, Germany



(image from doi: 10.1109/JSTARS.2016.2516041)

Soil moisture

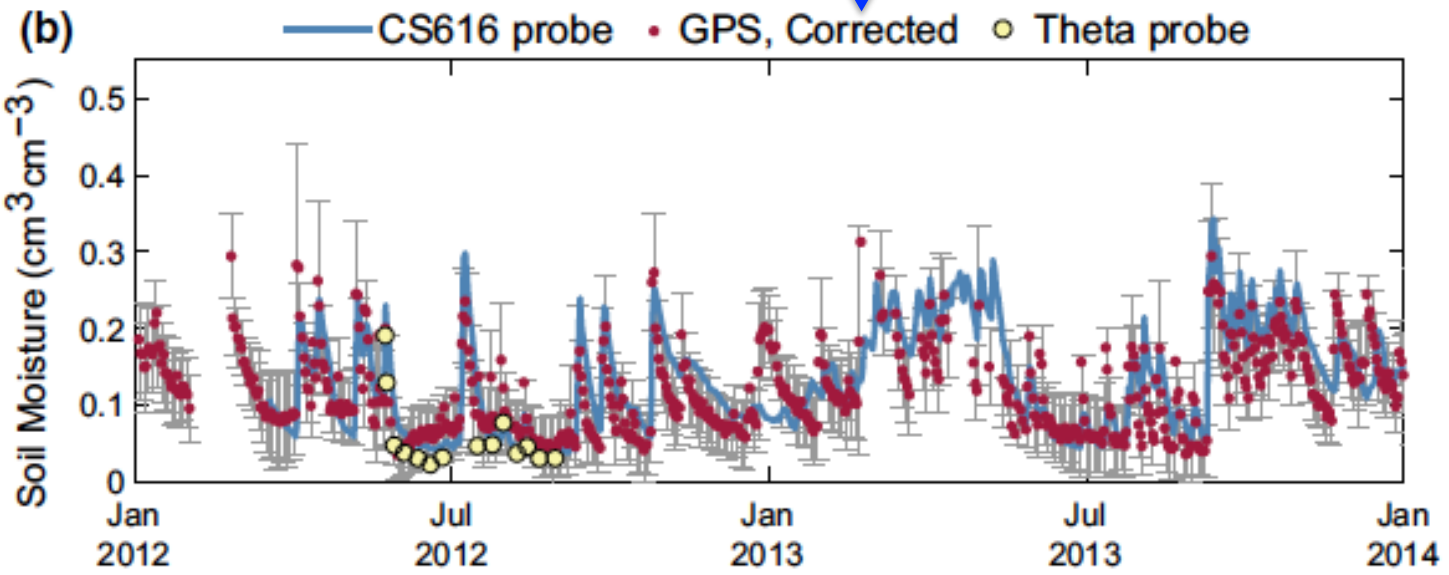
MFLE, Colorado, USA



(image from: doi:10.1007/s10291-015-0462-4)

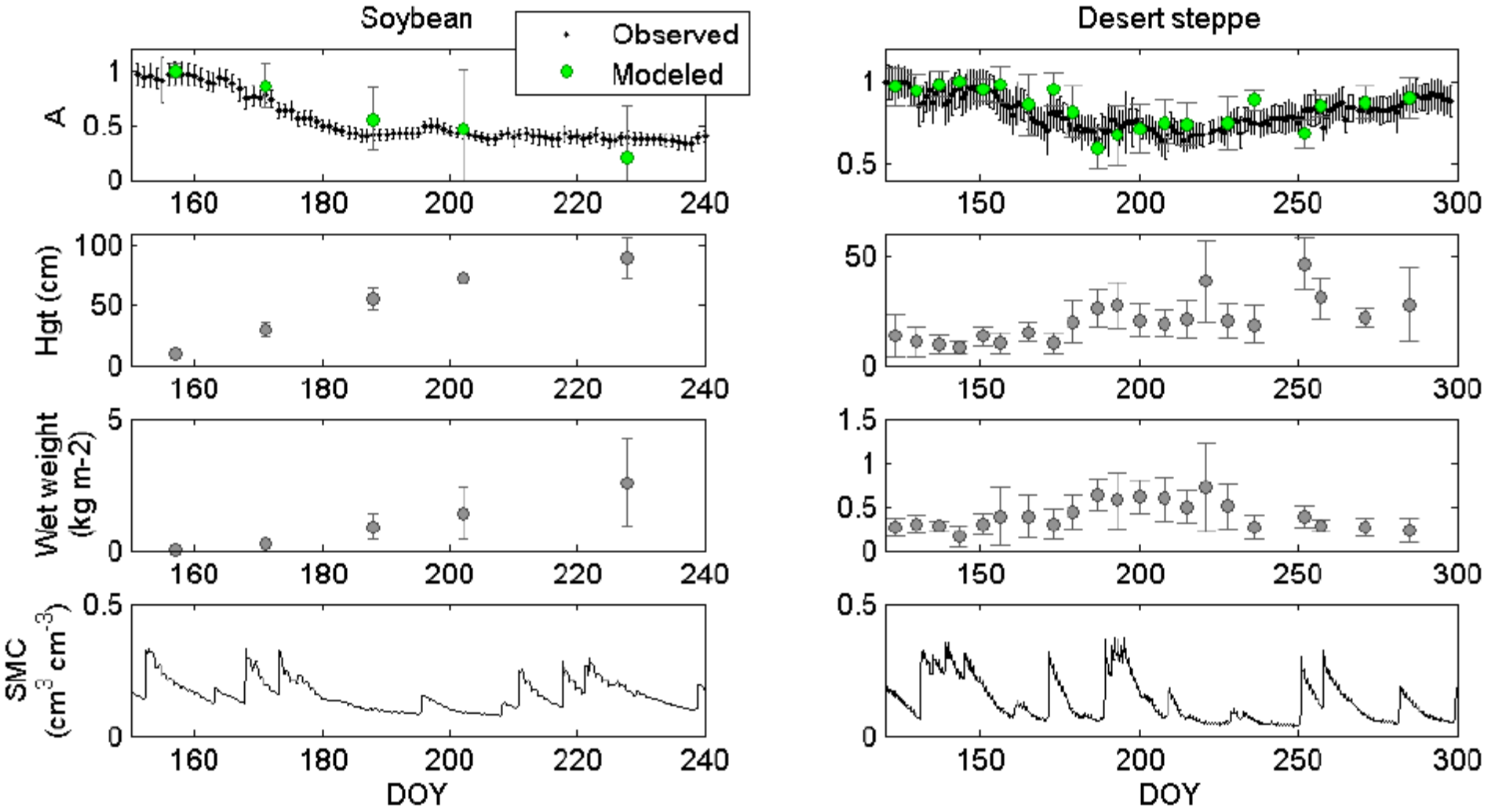
MFLE, Colorado, USA

Correction for vegetation!



(image from: doi:10.1007/s10291-015-0462-4)

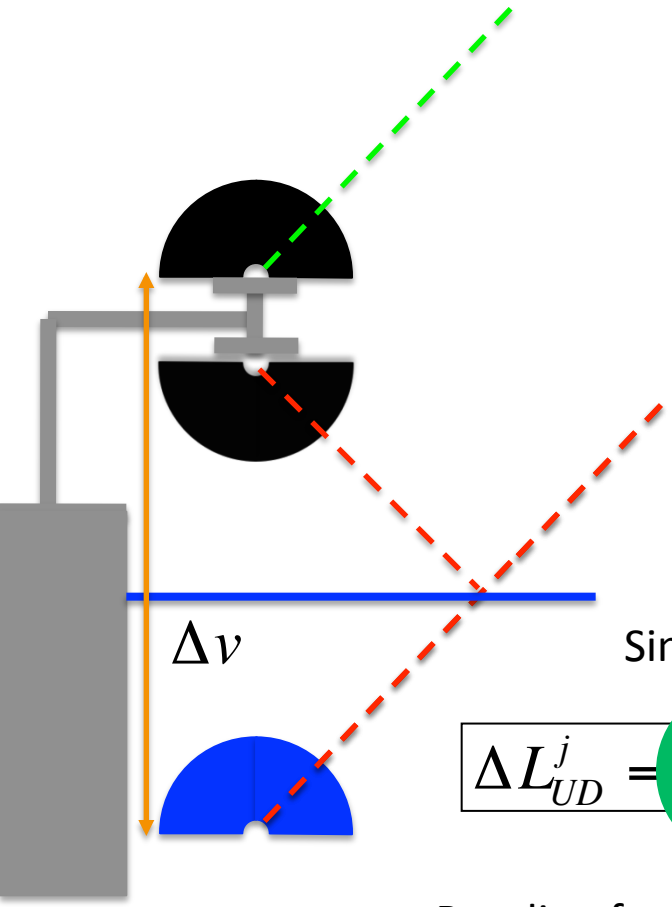
Vegetation



(image from http://xenon.colorado.edu/portal/publications/Chew_TGRS_rev.pdf)

Special installations I: Geodetic dual-antenna setup

Two-antenna GNSS-R phase tide gauge:



Phase measurement upward antenna / receiver (GTGU)

$$\lambda_0 \Phi_U^j = \rho_U^j + c\,(t_U - t^j) + Z_U^j - I_U^j + \lambda_0 N_U^j + \varepsilon$$

Phase measurement downward antenna / receiver (GTGD)

$$\lambda_0 \Phi_D^j = \rho_D^j + c\,(t_D - t^j) + Z_D^j - I_D^j + \lambda_0 N_D^j + \varepsilon$$

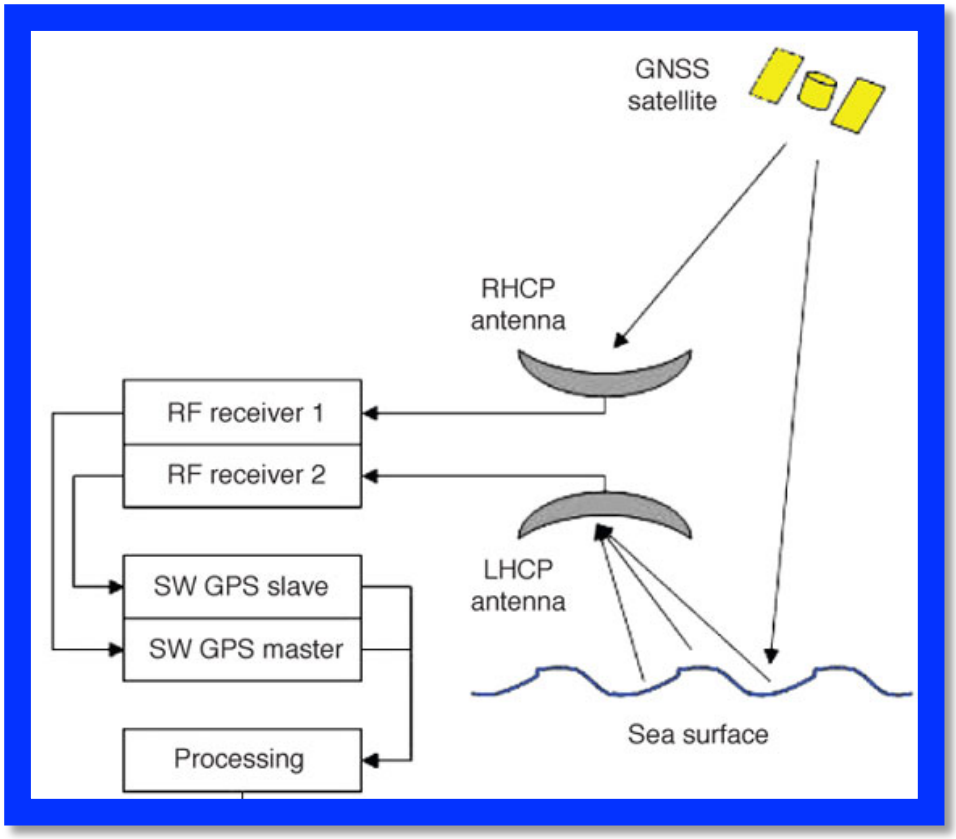
Single-difference

$$\Delta L_{UD}^j = \Delta \rho_{UD}^j + c\,\Delta t_{UD} + c\,(t^j - t^j) + \Delta Z_{UD}^j - \Delta I_{UD}^j + \Delta N_{UD}^j$$

Baseline for vertically aligned antennas

$$\Delta \rho_{UD}^j = \Delta e \sin(\alpha^j)\cos(\varepsilon^j) + \Delta n \cos(\alpha^j)\cos(\varepsilon^j) + \Delta v \sin(\varepsilon^j)$$

Special installations II: Dual-antenna setup for direct correlation



http://www.gpsworld.com/wp-content/uploads/2010/09/Fig1.jpg

http://www.insidegnss.com/auto/popupimage/WP-500PX.jpg

http://www.mdpi.com/remotesensing/remotesensing-04-02356/article_deploy/html/images/remotesensing-04-02356f2-1024.png

Requires dedicated (custom-built) hardware !!

Taking things to the next level

…

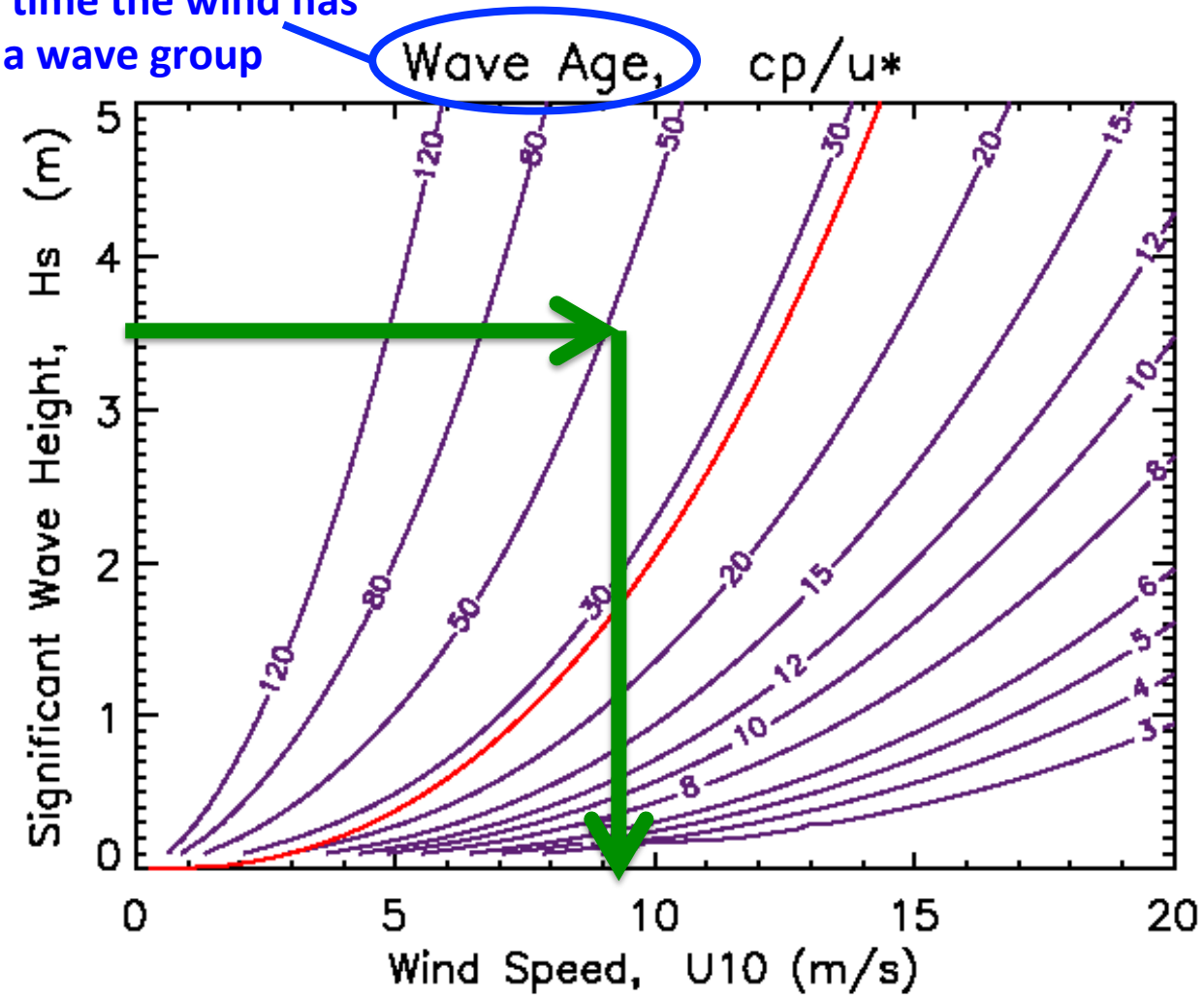
air- and spaceborne GNSS-R

Air- and spaceborne GNSS-R

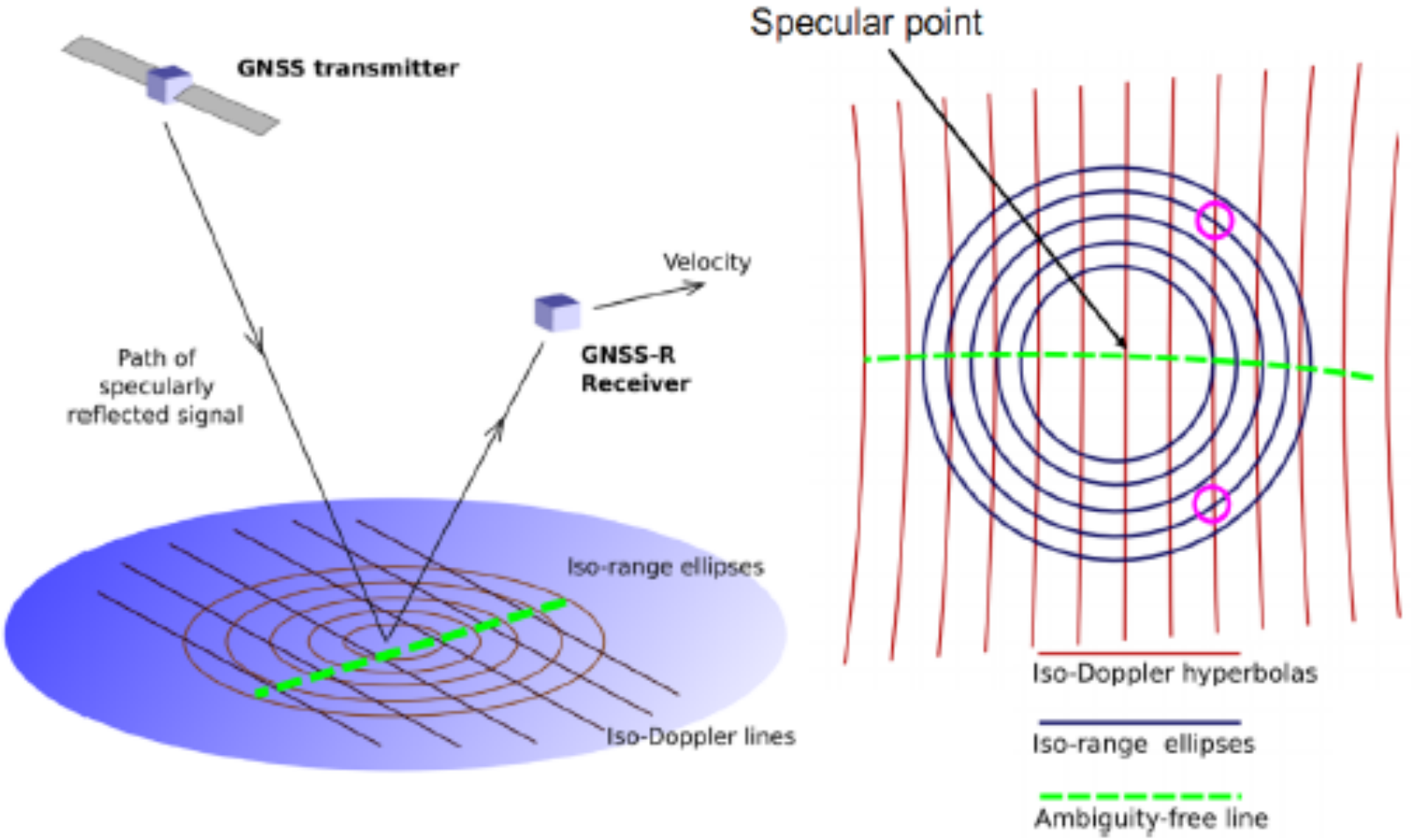
- Dedicated hardware
  - One GNSS receiver tracks direct signals
  - "GNSS-R receiver" tracks reflected signals
    - Provide Delay-Doppler information over certain integration period
    - (Usually) includes radiometric calibration
- Used for
  - Oceanography
    - Sea surface roughness/**wind speed**
    - Sea surface height
  - "classical parameters" (similar to those of ground-based systems)
    - soil moisture
    - vegetation
    - ice

Parenthesis

measure of the time the wind has been acting on a wave group

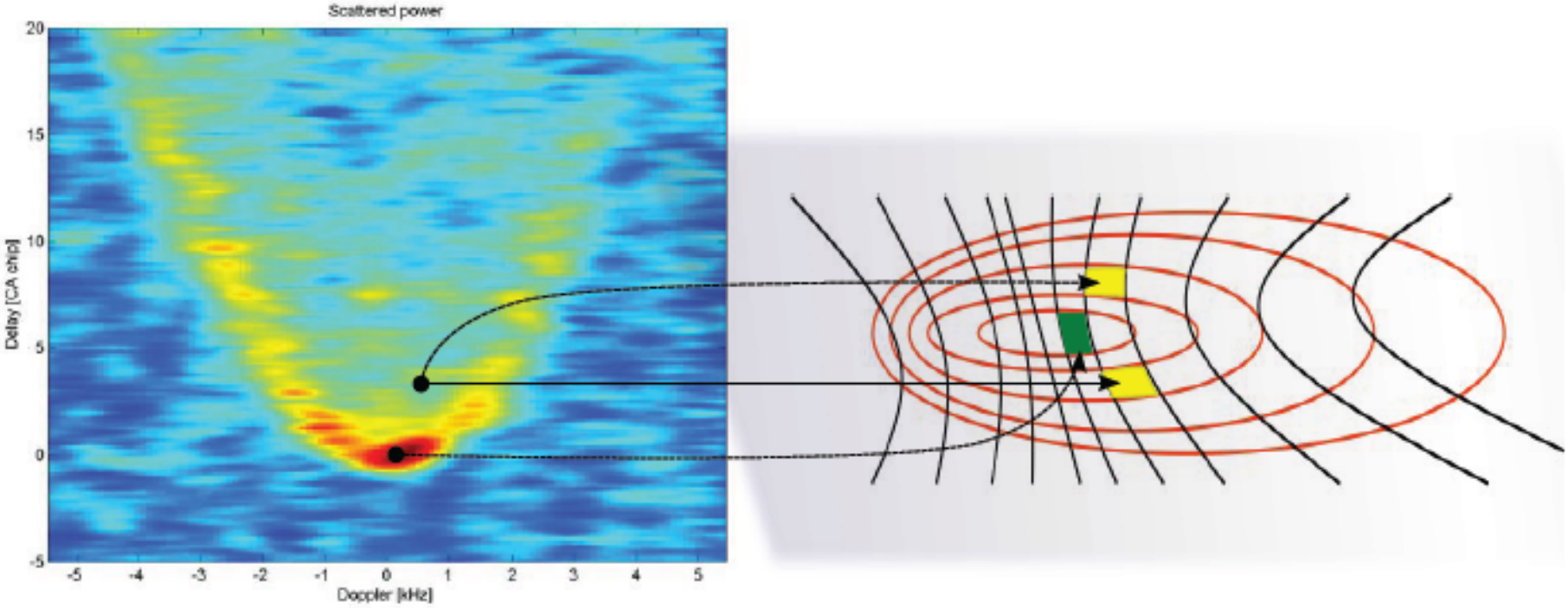


(source: http://coaps.fsu.edu/~bourassa/wa.n10.gif)

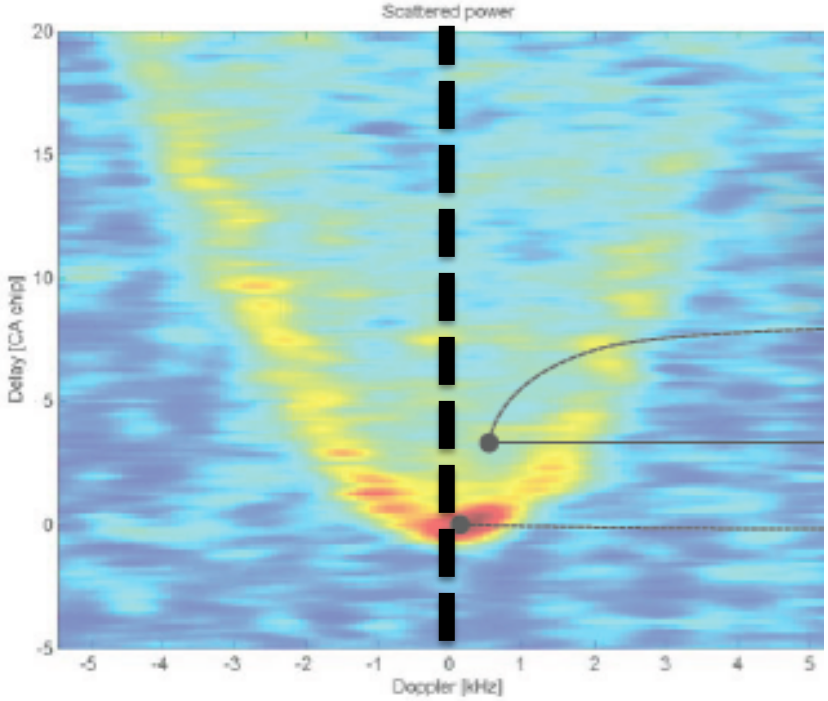


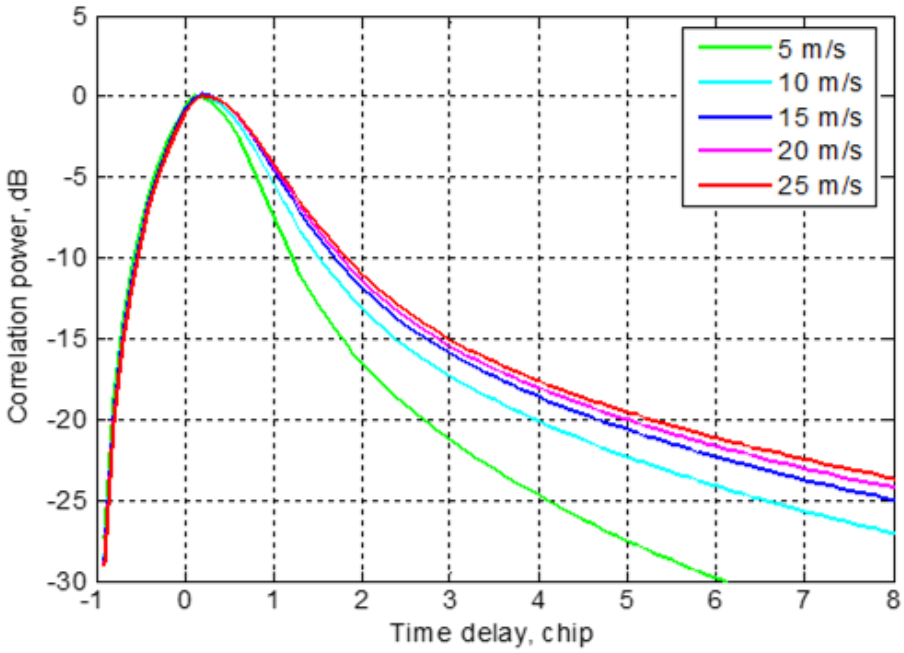
From: http://www.unoosa.org/pdf/icg/2012/icg-7/wg/wgc2-1.pdf

Delay-Doppler Map (DDM)



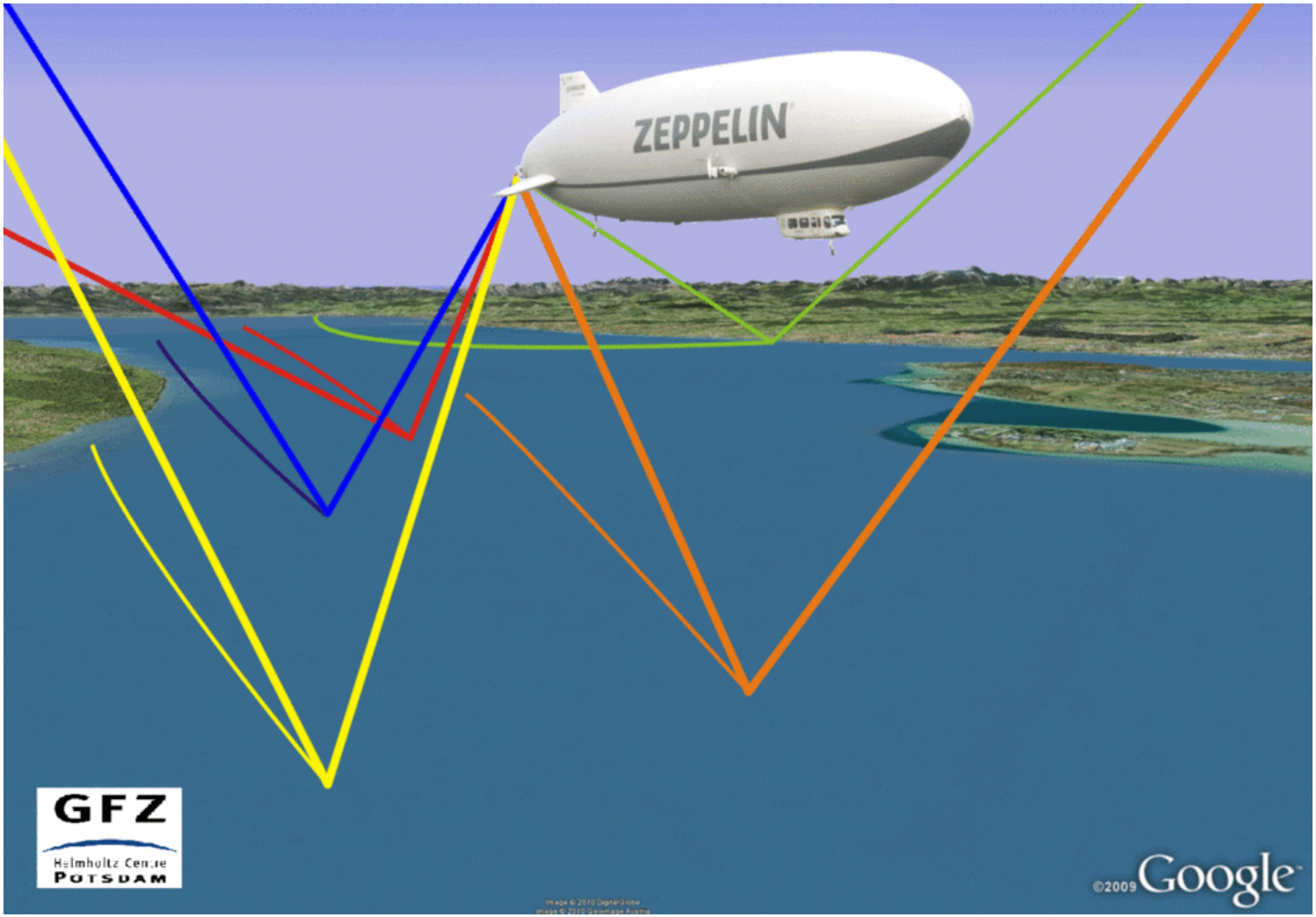
(from Unwin, M., et al., "The SGR-ReSI – A New Generation of Space GNSS Receiver for Remote Sensing", ION GNSS 2010, Portland, Oregon, Sept 2010.)





(from Unwin, M., et al., "The SGR-ReSI – A New Generation of Space GNSS Receiver for Remote Sensing", ION GNSS 2010, Portland, Oregon, Sept 2010.)

Examples for air-borne systems

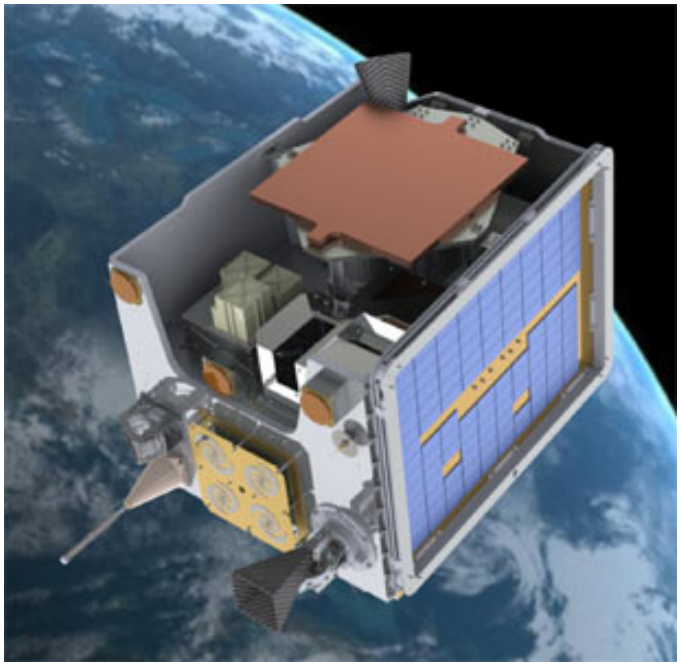


(http://www.gfz-potsdam.de/typo3temp/pics/zeppelin_Kopie_80e5400a84.gif)

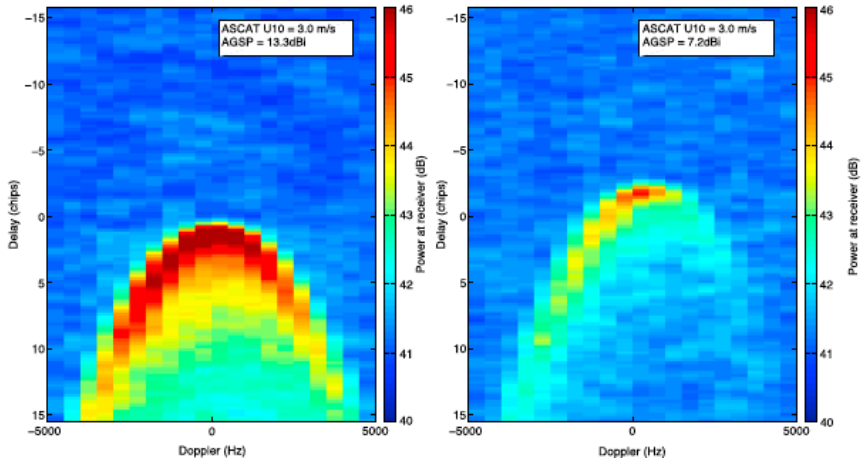
(source: http://www.ice.csic.es/research/gold_rtr_mining/imagenes/campaigns/test_1.jpg)

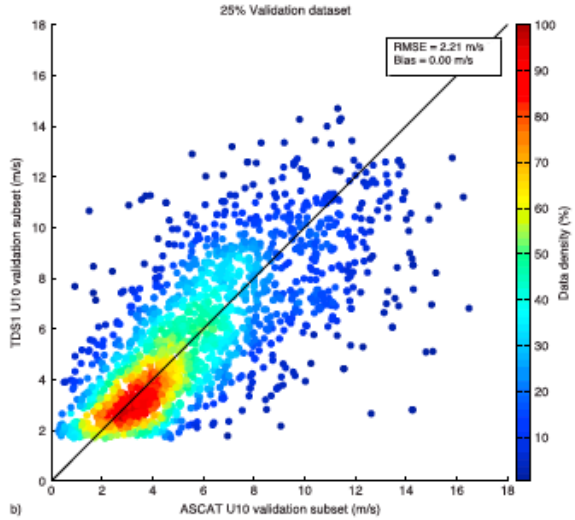
Spaceborne missions

TechDemoSat-1: Launched 2014



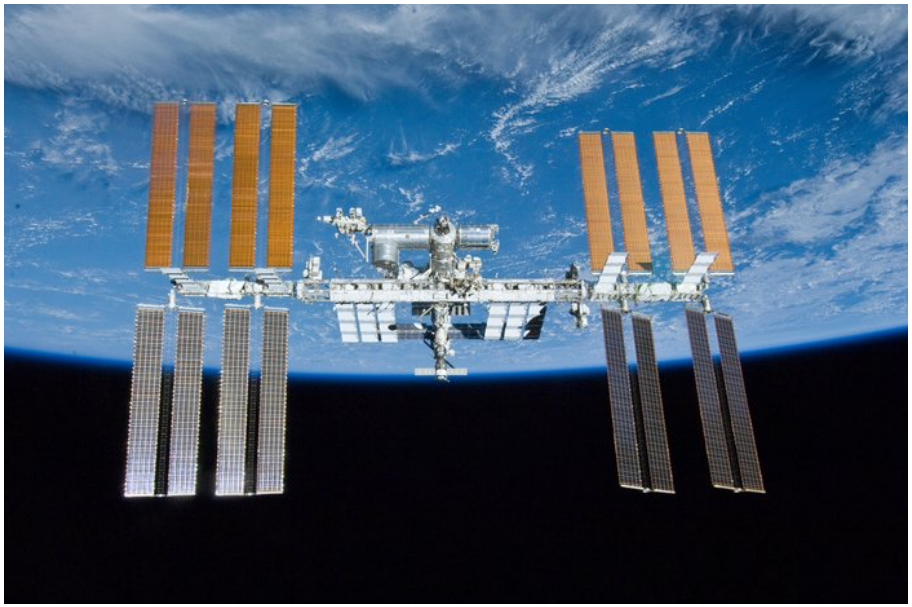
(source: http://space.skyrocket.de/img_sat/techdemosat-1__1.jpg)



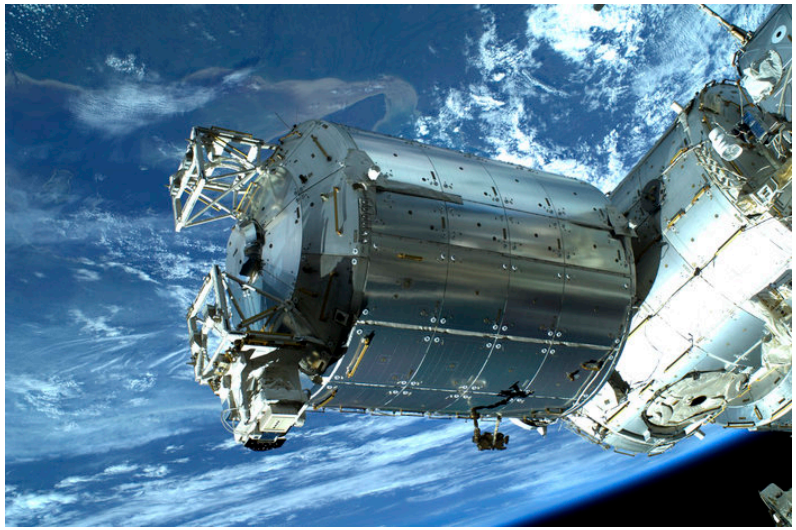


(images from doi:10.1002/2015GL064204)

GEROS ISS: expected for late 2019

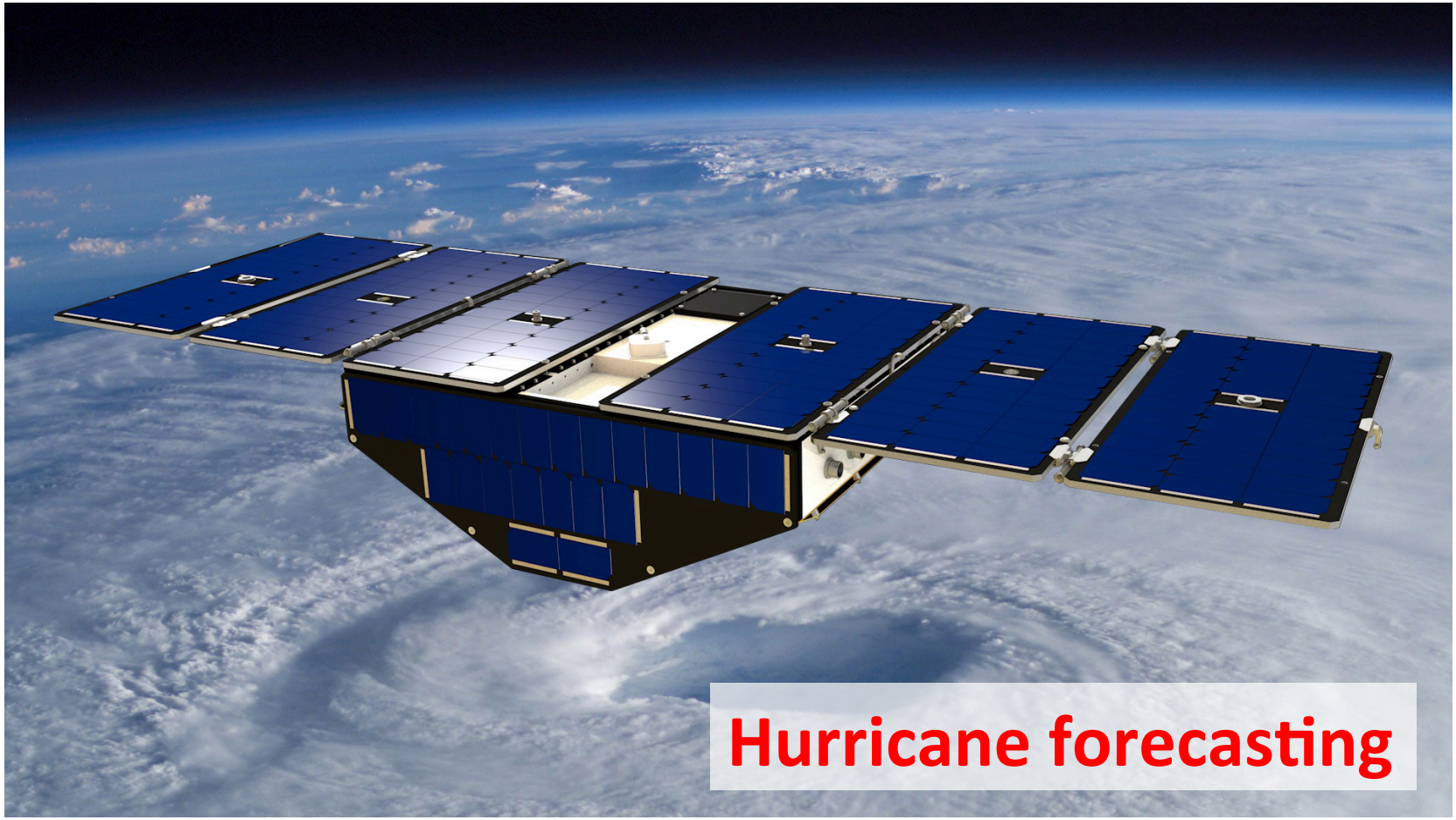


(source http://www.esa.int/var/esa/storage/images/esa_multimedia/images/2015/03/iss_for_earth_science/15310597-1-eng-GB/ISS_for_Earth_science_node_full_image_2.jpg)



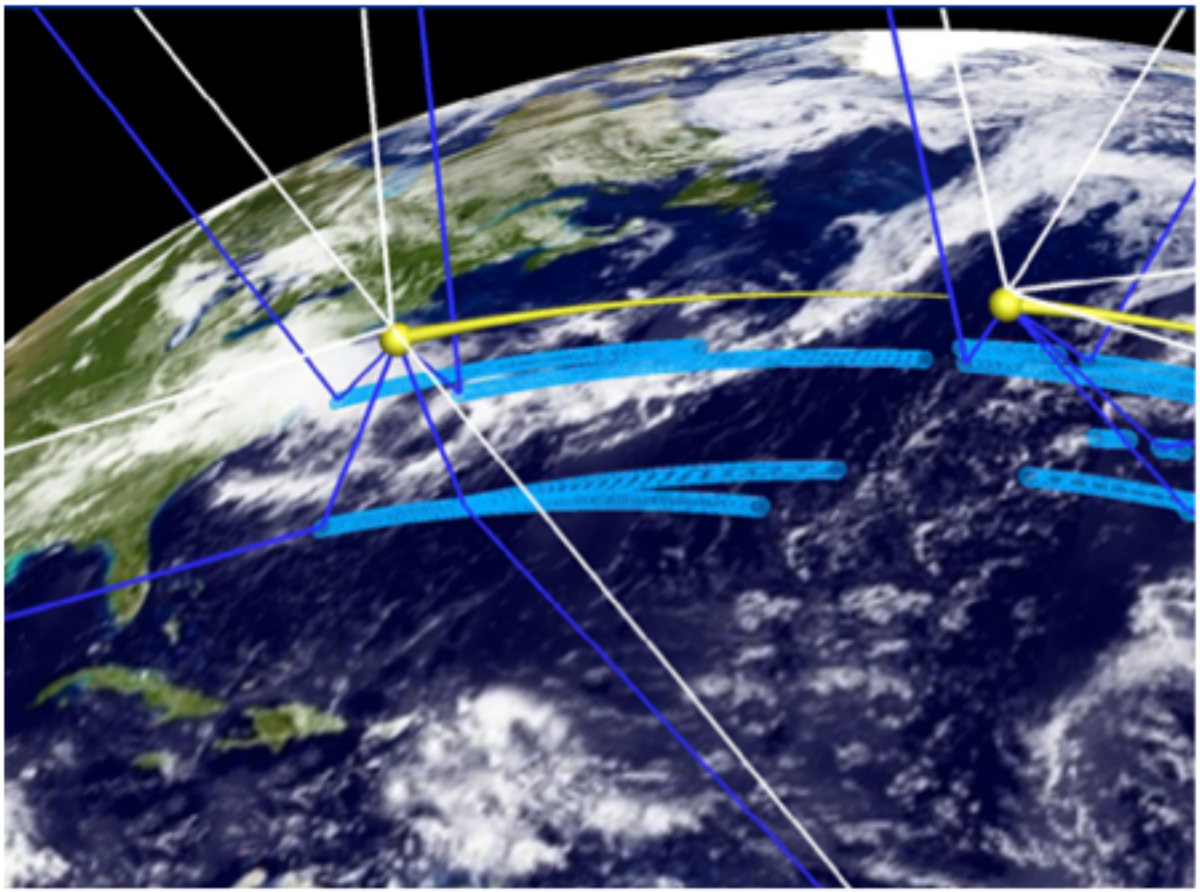
(source: http://www.esa.int/var/esa/storage/images/esa_multimedia/images/2013/07/flying_over_columbus_i_m_the_farthest_away_from_earth/12941722-6-eng-GB/Flying_over_Columbus_I_m_the_farthest_away_from_Earth_node_full_image_2.jpg)

CYGNSS: launch in October 2016!

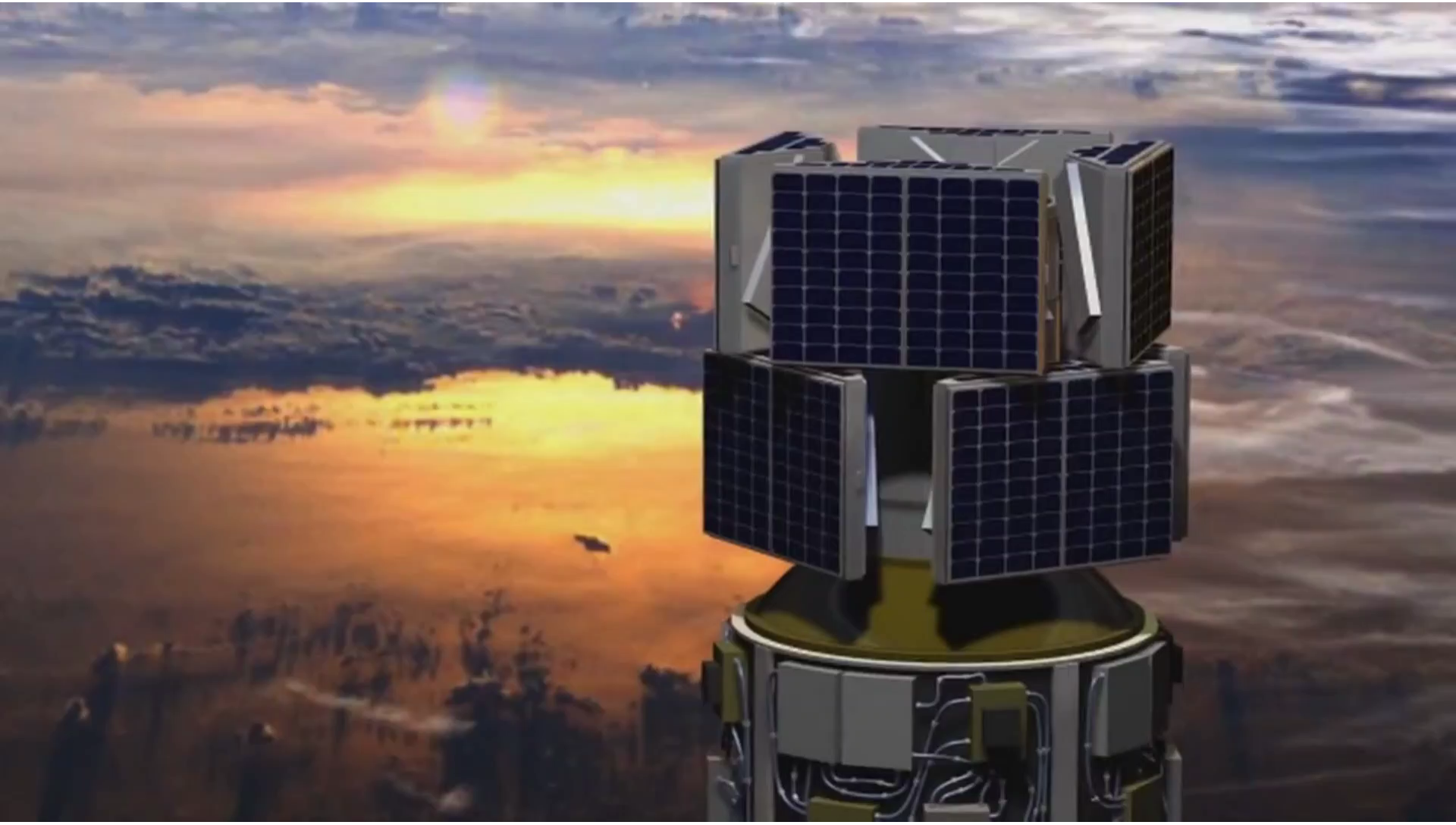


(source: http://www.nasa.gov/sites/default/files/thumbnails/image/cygnss-inorbit-artconcept_002.jpeg)

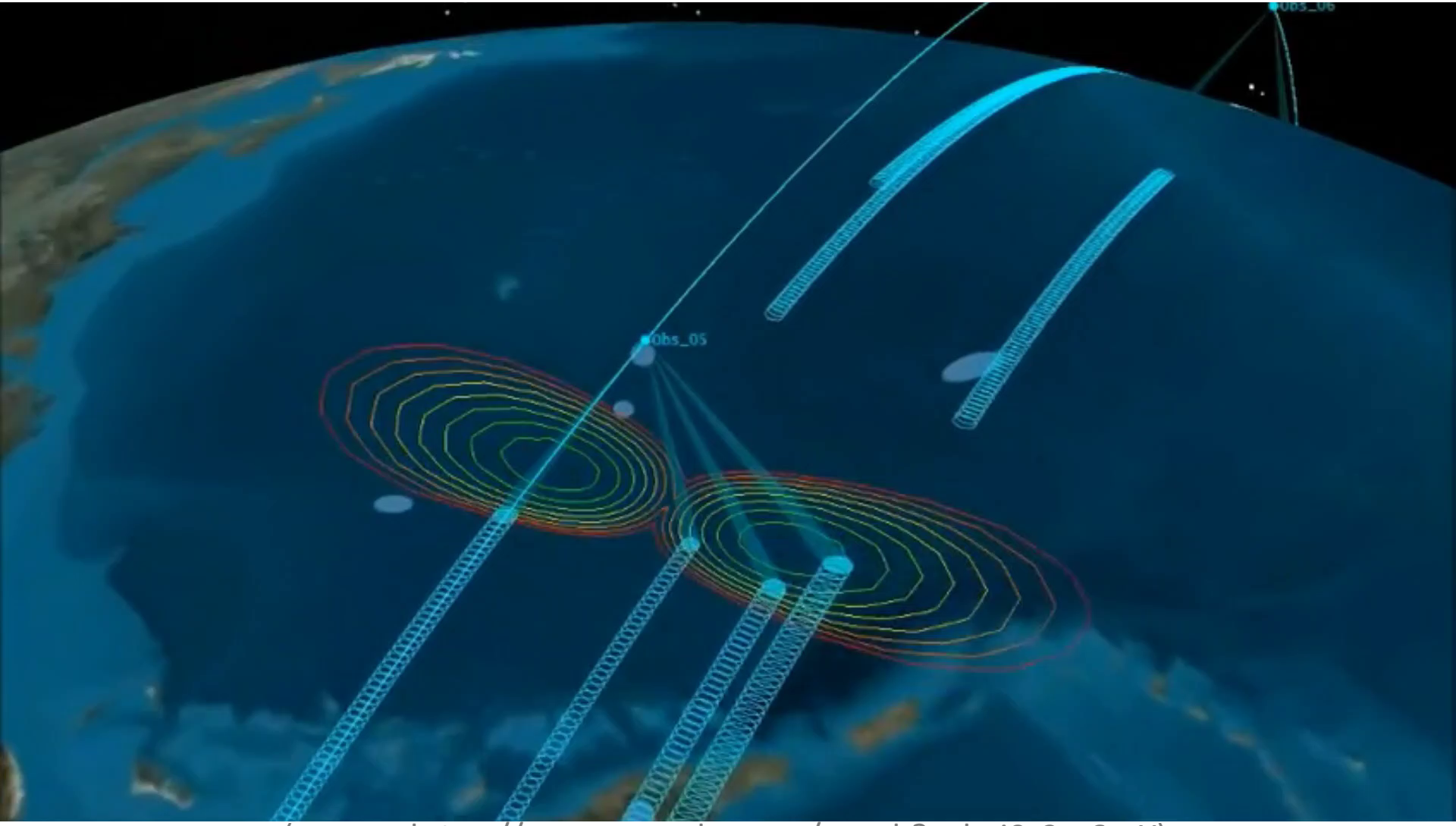
CYGNSS: 8 satellites in 500 km circular orbits at an inclination of ~35 deg



(source. http://science.nasa.gov/media/medialibrary/2013/01/03/cygnss2.png)



(from: https://www.youtube.com/watch?v=rRBqn6JPtv8)



(source: https://www.youtube.com/watch?v=bei0s3m6vcY)

Ground-based GNSS-R

- "Accidental sensor" when using existing GNSS infrastructure
  - Sea level, Ice and snow
  - Soil moisture and vegetation
- Only a few sites with dedicated HW
  - More will appear

Air- and spaceborne GNSS-R

- Dedicated HW, produces mainly DDMs
- Novel sensor for
  - Ocean winds, currents, heights and sea surface conditions
  - Also for soil moisture and cryosphere studies

Thank you very much for your attention!

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