INSAR-GEODESY AND GEODETIC INFRASTRUCTURE

TRANSPONDERS AND REFLECTORS

Hans van der Marel, Ramon Hanssen

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WHY USE REFLECTORS AND TRANSPONDERS?

Improve spatial sampling

Connect InSAR & other techniques

The main strength of InSAR is that it is an opportunistic technique: it does not require any advanced planning and installation of markers in the field.

So then, why use reflectors and transponders? There are two main reasons to install a reflector or transponder:

1. Improve spatial sampling in areas where there are no natural persistent scatterers
2. Connect InSAR and other techniques

   2A Connection between different tracks of the same InSAR system, and/or, connection between different InSAR systems

   2B Connection between InSAR and other techniques (e.g. GNSS) → make InSAR “absolute”

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WHY DO WE NEED REFLECTORS AND TRANSPONDERS TO CONNECT INSAR?

- Answer, we don't necessarily have to, we can also use natural persistent and coherent scatterers, but co-located instruments have advantages.
- There two options
    1. Use natural persistent scatterers. These are not the same EM points for different tracks and systems, but the tracks and systems can be combined using the (first moment of) estimated velocity of the disjunct scatterers in the same area. The strength of this technique comes in numbers (of scatterers). Combination in the parameter space.
    2. Use artificial scatterers (transponders and reflectors) with the same EM point in different tracks and for different systems. The deformation time-series (and velocity) should be the same for each track and system (after conversion for line-of-sight direction). The strength of this technique comes from the well-identifiable reflector or transponder. Combination in observation space.
- For the connection between InSAR and other techniques the artificial scatterer must be integrated with other equipment, e.g. a GNSS receiver.
- For the best results a mechanical connection between the instrumentation at one site should be used.

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CORNER REFLECTORS

- Passive devices
- Always on

✔ simple
✔ phase stable
✔ all systems, frequencies, polarizations

✖ big / heavy
✖ autonomous motion

✖ multi-year reliability (e.g. conspicuous, vandalism)
✖ maintenance (e.g. clogging, snow, rain)
✖ single satellite pass (either ascending or descending)

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TRANSPONDERS

- Electronic (active) devices

✔ small, compact and light
✔ ascending/descending orbits in one unit

✖ Selective (C/X band, polarization, on-time)
✖ Need (battery) power

? radar cross section ?
? phase stable ?
? multi-year reliable ?
? maintenance ?
? cost and availability ?
? license?

✓ or ✗

Size ~ shoe box

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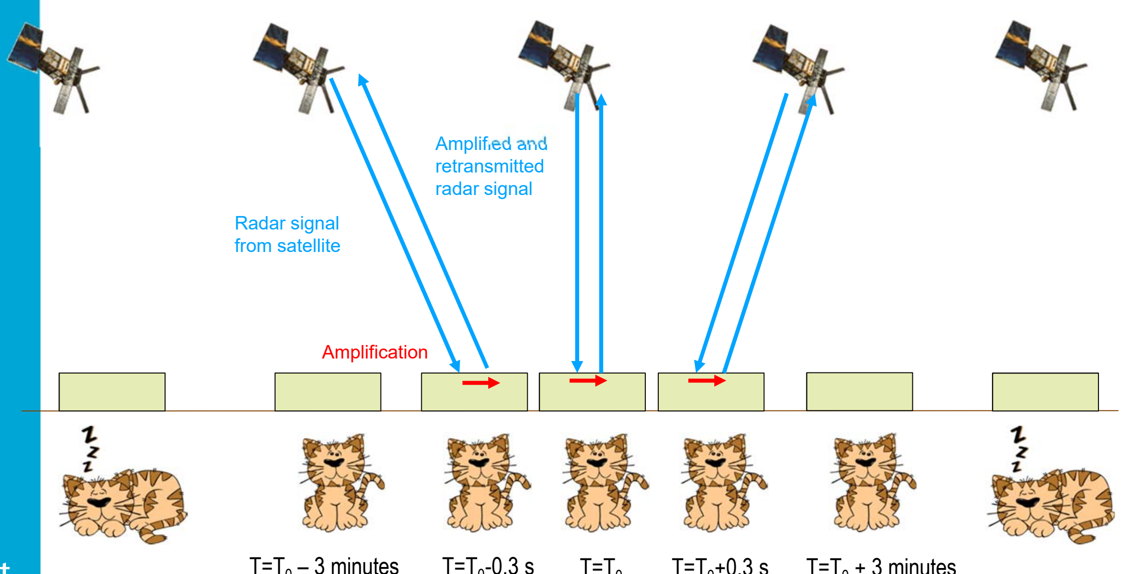
HOW TRANSPONDERS WORK



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TRANSPONDER EVENTS AND PROGRAMMING

Transponder on-time $T = (T_0 – T_{warmup} - 0.5*T_{on\text{-}window}) \ldots (T_0 + 0.5*T_{on\text{-}window})$

- T_0 predicted zero-Doppler overpass time
- $T_{on\text{-}window}$ nominal transponder on-time
  - Actual overpass few milliseconds
  - Safety margin of few tens of seconds up to minutes for predicted T_0 to account for prediction accuracy and drift in true zero-Doppler overpass time
  - Safety margin to account for the clock drift of the transponder
- T_{warmup} time needed for the transponder to “warm-up” (manufacturer dependent)

Transponders on-times can be uploaded via a serial interface to the transponder

- Calendar format with date and time of each event
- Format with start data, time and repeat period of each event

Set of Matlab™ scripts to compute the T_0 and several calendar format (CAT, MUTE, ECR) from (i) Doris res files, (ii) precise orbit files, and/or (iii) NORAD two line elements (TLE).

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TRANSPONDER EVENTS AND PROGRAMMING

- The accuracy of the zero-Doppler prediction is a few seconds with the Matlab scripts
- But, this makes little sense if the clock inside the transponder is not synchronized to UTC.
- The Matlab scripts have an option to take a correction for clock drift into account, but the correction itself is hard to compute and requires regular inspection of the clock error of the device.
- For the CATs we used a 6 minute window and corrected the on-times for the transponder clock drift.
- For the other transponders, which use GPS to synchronize their clock to UTC, a shorter window is sufficient. For the ECRs we used a 1 minute window.

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TRANSPONDER FIELD TESTS

Different satellites and validation techniques

Delft (NL):	Slovenia:	Wassenaar (NL):
ERS-2	Envisat	Radarsat-2, Sentinel-1, TSX, CSK
Levelling	Collocated GPS	Levelling and Ref CR
2011	2011-2012	Since 2013

In addition to the transponder experiments at the IJmuiden, Eijsden and Vlissingen EUREF permanent GPS stations 2012-2015 (Radarsat-2).

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I2GPS FIELD TEST (SLOVENIA)

InSAR Transponder with integrated GPS

Landslide area

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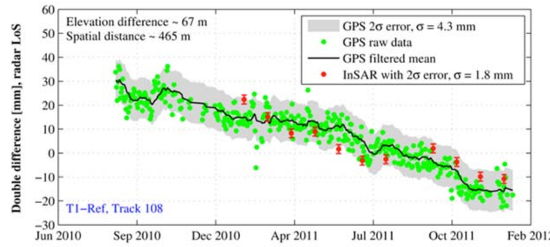
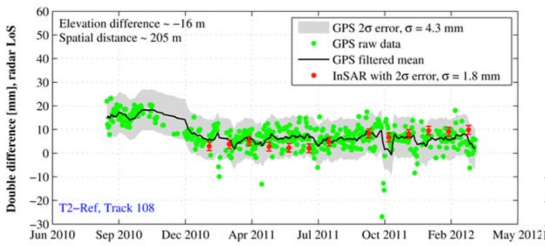
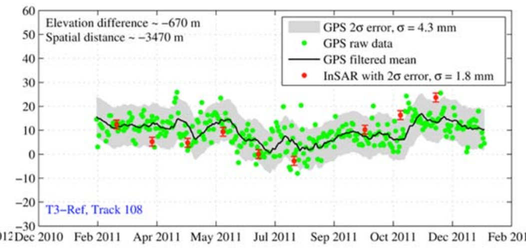
I2GPS FIELD TEST (SLOVENIA)

- GPS σ = 4.3 mm
- Transponder σ = 1.8 mm
- Envisat was in a decaying orbit







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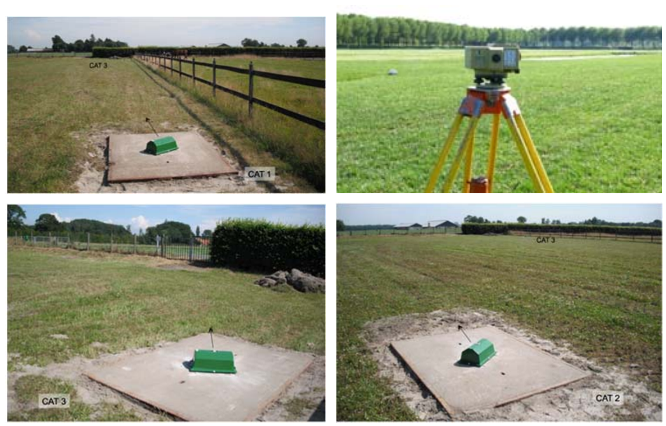
CAT TESTING AT WASSENAAR TEST SITE

InSAR transponder with levelling

2013-2015



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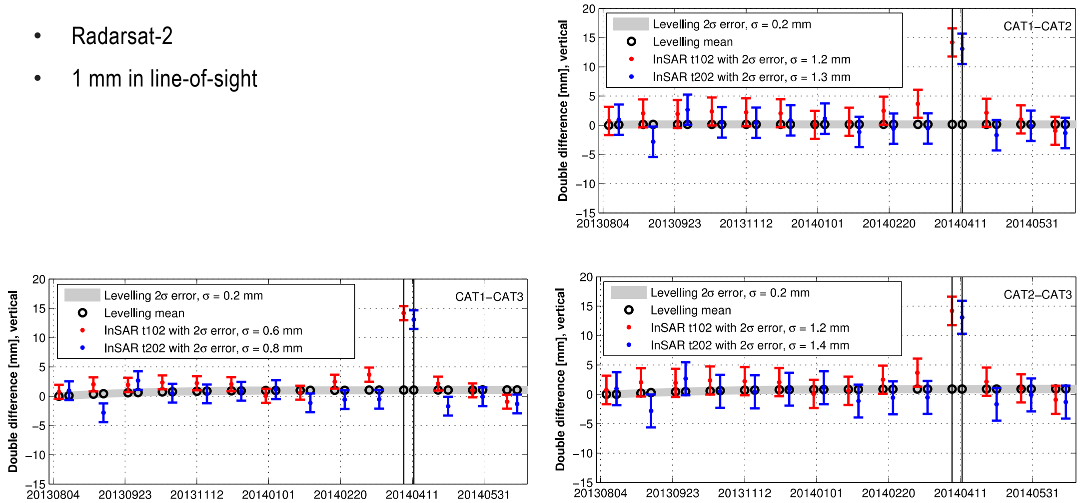
RESULTS OF CAT TESTING

- Radarsat-2
- 1 mm in line-of-sight



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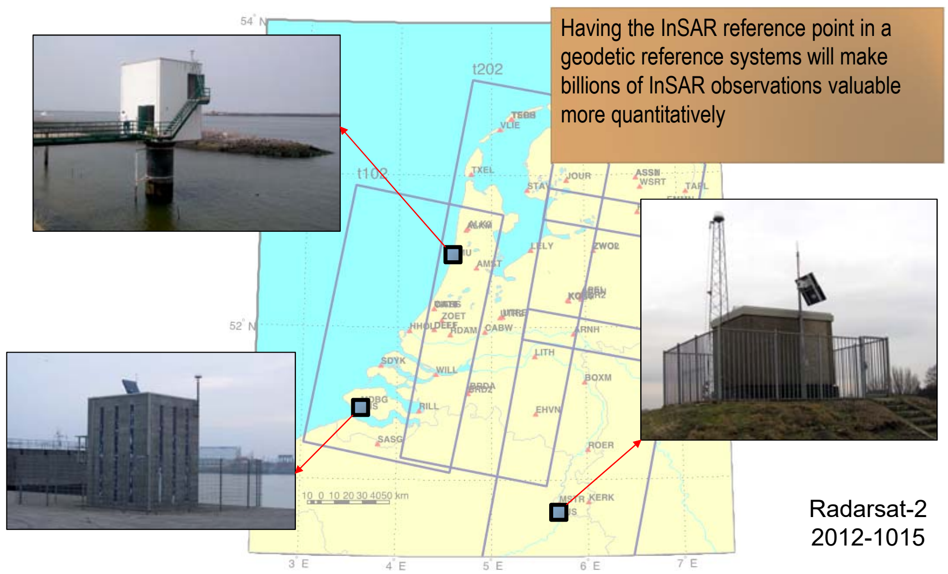
EXPERIMENTS AT EPN GNSS STATIONS IN NL

Having the InSAR reference point in a geodetic reference systems will make billions of InSAR observations valuable more quantitatively



Radarsat-2
2012-1015

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CAT IJmuiden

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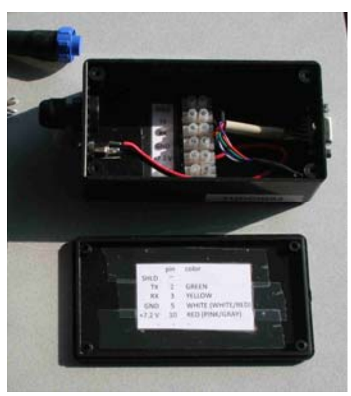
CAT INTERFACE (@ PERMANENT SITES)



Trickle charge CAT battery
RS-232 Interface to CAT

Access to roof is difficult

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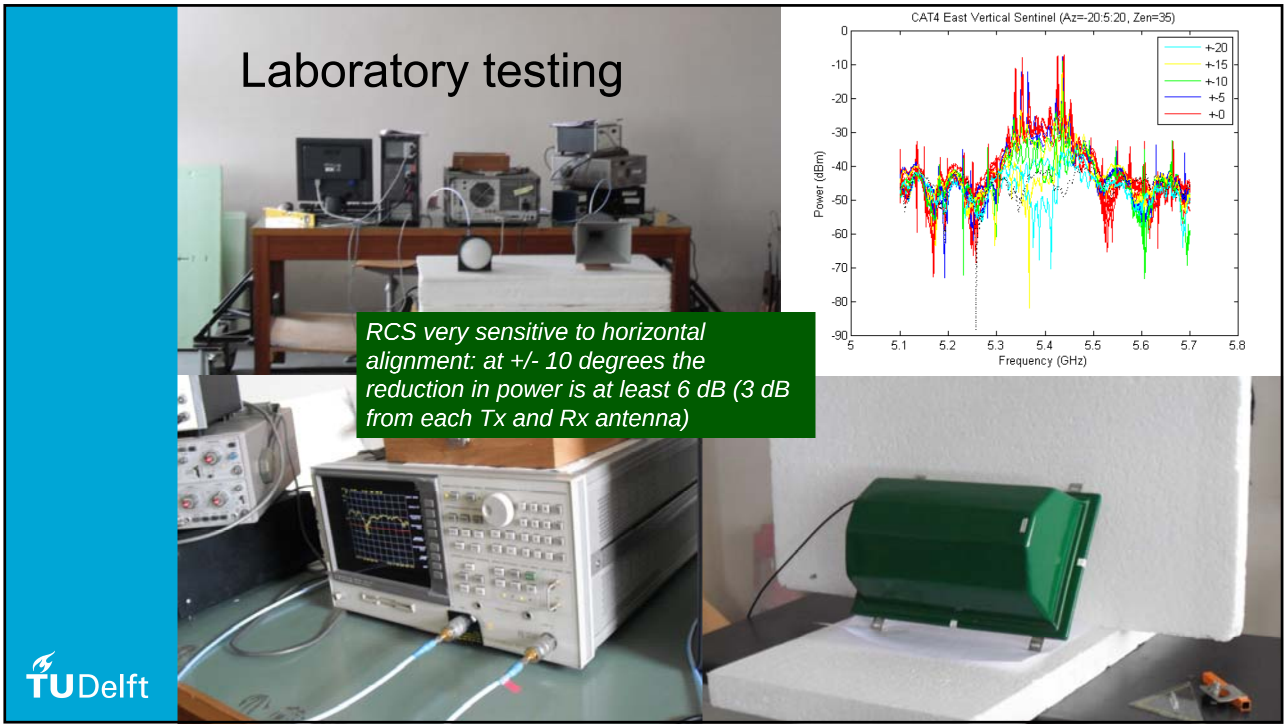
Laboratory testing
CAT4 East Vertical Sentinel (Az=-20:5:20, Zen=35)
+-20
+-15
+-10
+-5
+-0
Power (dBm)
Frequency (GHz)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
5
5.1
5.2
5.3
5.4
5.5
5.6
5.7
5.8
RCS very sensitive to horizontal alignment: at +/- 10 degrees the reduction in power is at least 6 dB (3 dB from each Tx and Rx antenna)
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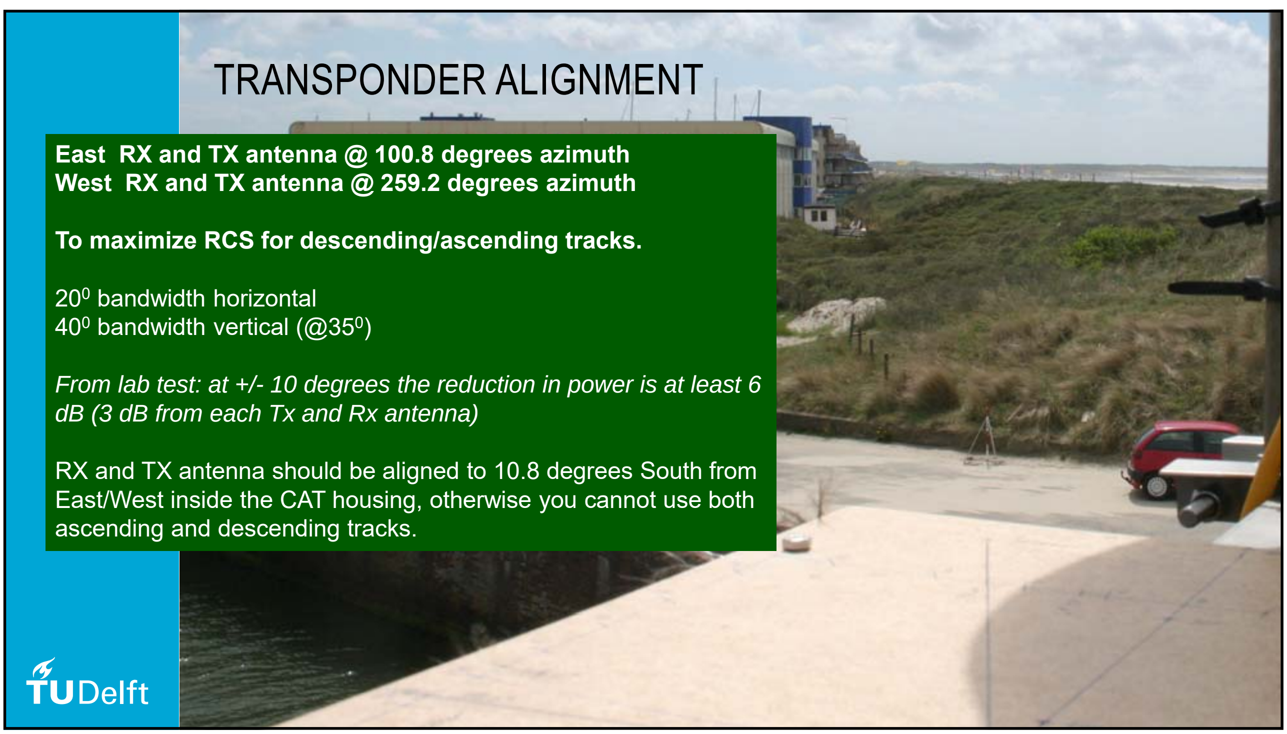
TRANSPONDER ALIGNMENT
East RX and TX antenna @ 100.8 degrees azimuth
West RX and TX antenna @ 259.2 degrees azimuth
To maximize RCS for descending/ascending tracks.
20⁰ bandwidth horizontal
40⁰ bandwidth vertical (@35⁰)
From lab test: at +/- 10 degrees the reduction in power is at least 6 dB (3 dB from each Tx and Rx antenna)
RX and TX antenna should be aligned to 10.8 degrees South from East/West inside the CAT housing, otherwise you cannot use both ascending and descending tracks.
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TRANSPONDER BRIGHTNESS ANALYSIS TOOLS

Matlab scripts to analyze Beta0

150x150m or 300x300m crops around a specified geographic position
Geolocation with radar coordinates
Overlays on Google Earth
- Multiimage Reflectivity Map (MRM)
- Animations
Relation to RCS

Can be used to analyze CAT performance

Can be used to select new sites for CATs

Some results are given on next slides.

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RCS COMPUTATION

- Calibrated Beta0 is computed from calibration factor and digital number

$$\beta^0 = \frac{1}{k_{S1}^2} \cdot |\mathrm{DN}|^2, \qquad \mathrm{DN} = \sqrt{I^2 + Q^2}.$$

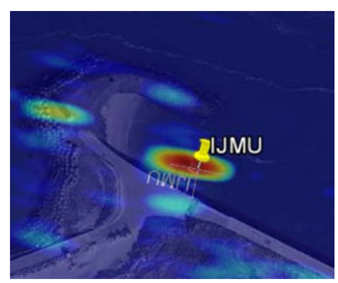
Beta0 can be expressed also in dB.

- RCS is computed from peak value of Beta0 and the resolution area

$$\mathrm{RCS} = 10 \cdot \log_{10}\left(\beta^0 \cdot \Delta_a \cdot \Delta_r\right),$$

Δ_a and Δ_r are the azimuth and slant range resolution

The unit for RCS is dBm2



Oversampled image

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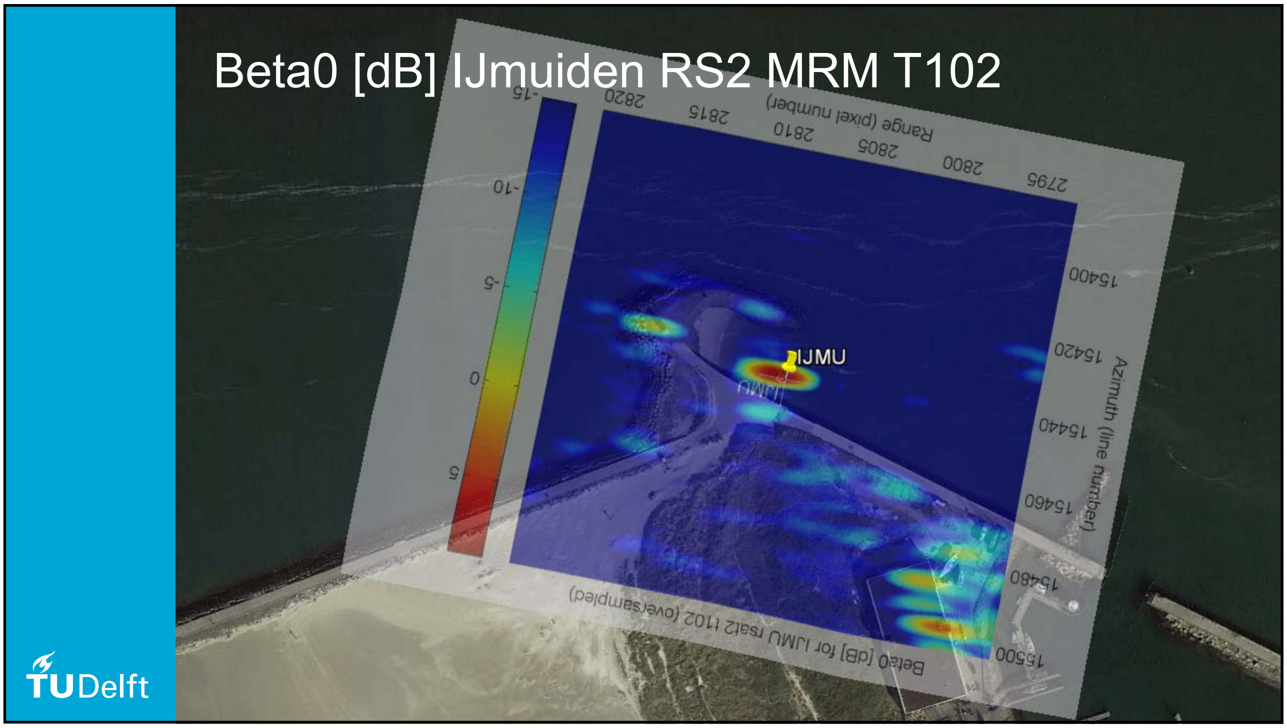
Beta0 [dB] IJmuiden RS2 MRM T102
IJMU
Range (pixel number)
Azimuth (line number)
Beta0 [dB] for IJMU rsat2 t102 (oversampled)
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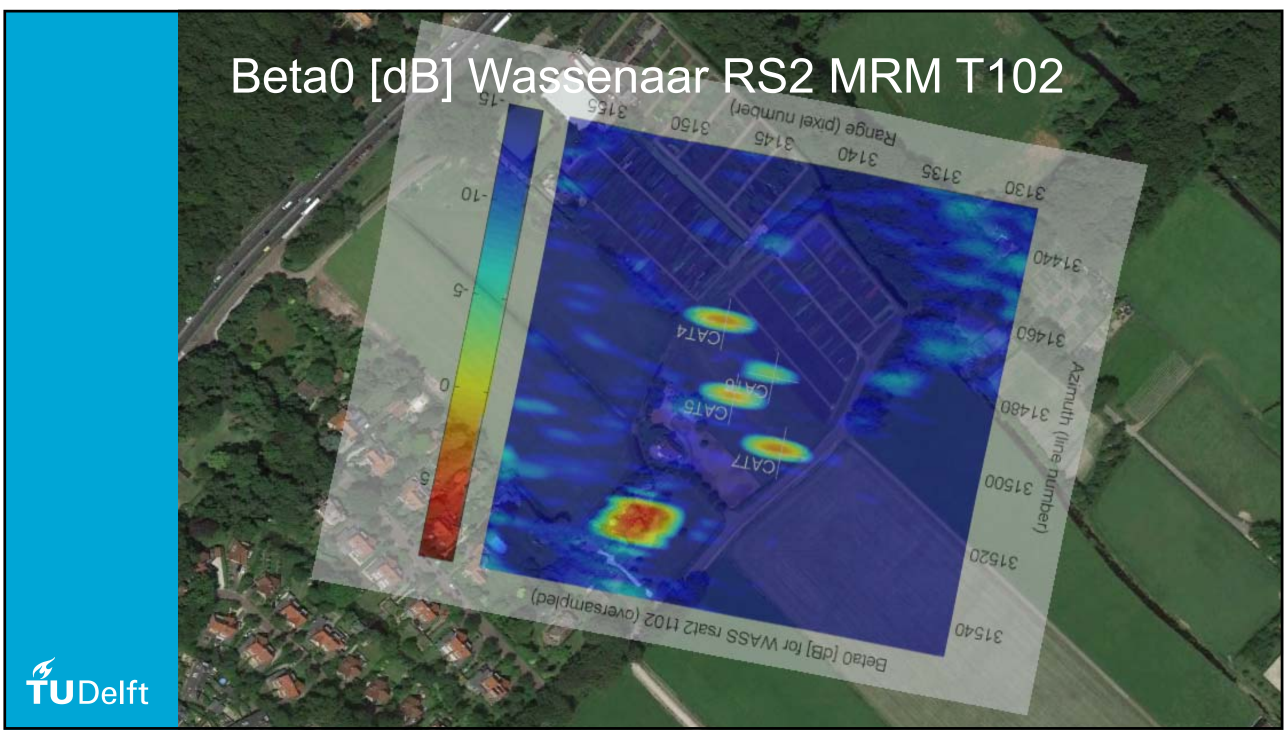
Beta0 [dB] Wassenaar RS2 MRM T102
CAT4
CAT5
CAT7
Range (pixel number)
Azimuth (line number)
Beta0 [dB] for WASS rsat2 t102 (oversampled)
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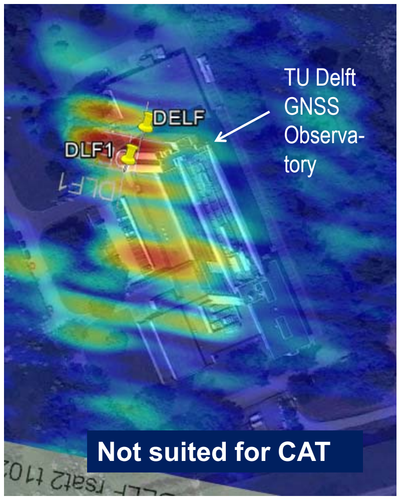
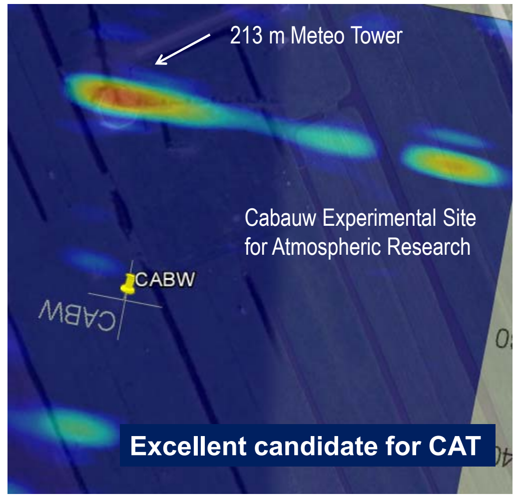
GNSS PERMANENT SITE RECONNAISSANCE





http://gnss1.tudelft.nl/pub/cats/gps_rsat2_300m.kmz (all stations)
http://gnss1.tudelft.nl/pub/cats/rsat2_XXXX_YYYY_300m.kmz (animated)

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IS IT FEASIBLE?

- ? Visibility ?
- ? Phase stability ?
- ? Multi-year reliability ?
- ? Maintenance ?

- ? Cost?
- ? Availability (commercial off-the-shelf) ?
- ? Licensing ?

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IS IT FEASIBLE?

? Visibility ? → **Yes (more power would help)**

? Phase stability ? → **Yes, comparable to CR**

? Multi-year reliability ? → **Yes, limited testing**

? Maintenance ? → **Modest**

? Cost ? → **<1000 EUR if mass production**

? Availability (commercial off-the-shelf) ? Not in 2015...

? Licensing ? → **Solvable**

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LESSONS LEARNED FROM EARLY CAT EXPERIMENTS

RCS (Radar brightness) of CATs is critical

Alignment of CAT is critical

- Alignment inside CAT tuned for latitude? E.g. rotate by 10.8 degrees to use both ascending and descending tracks
- Other design changes (TX and RX on either side of mast)?

More flexible mounting options

- CAT must be able to be removed for servicing and installed back at exactly same location
- Batteries should be replaceable / charged in the field
- Remote connection to CAT *)
- Power connection (remotely controlled charger *))

*) can be done outside CAT

Quick look analysis to check if CATs have transponded

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RECENT DEVELOPMENTS

Transponders

- Testing of a new transponder system (MUTE) – ESA project [2016-2017]
- Testing of commercially available transponders from MetaSensing [2017-…]

Corner Reflectors

- Development of Integrated Geodetic Reference Station (IGRS) [2017-2018]
  - Double BackFlip Conner Reflector Design
  - Integrated with GNSS receiver

Our strategy is to develop both transponders and Corner Reflector systems

- Transponders best suited for installation at existing permanent GNSS stations
- IGRS system best suited (currently) for new installation

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MUTE TRANSPONDER TESTS [2016-2017]

- Two devices, MUTE-1 and MUTE-2, installed (Space Engineering, Rome)
- Reference Corner Reflectors (next slide)

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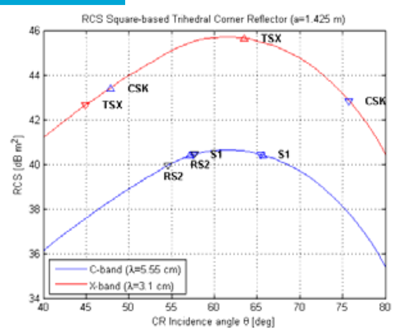
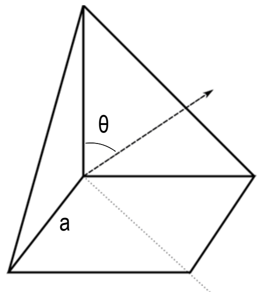
REFERENCE CORNER REFLECTOR



- Square-based trihedral corner reflector



a = 1.425 m
θ = 61.42 deg *)

max A_{eq} = 1.69 m^2 *)

$$RCS = 4\pi \frac{A_{eq}^2}{\lambda^2}$$

	max RCS
C-band	40.65 dB
X-band	45.71 dB

- One for descending, one for ascending
- Alignment on average of Sentinel-1 tracks

*) Groot, J. (1992), Letter: Cross Section Computation of Trihedral Corner Reflectors with the Geometrical Optics Approximation. Eur.Trans.Telecomm., 3:637-642. doi:10.1002/ett.4460030618

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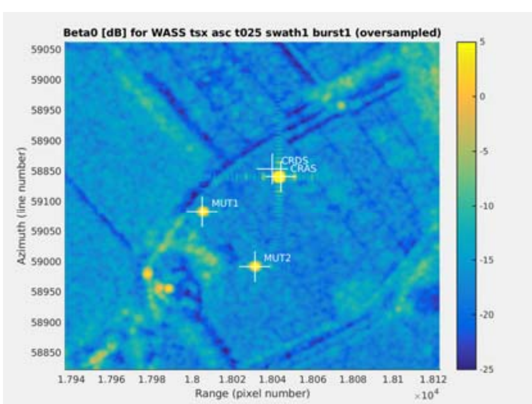
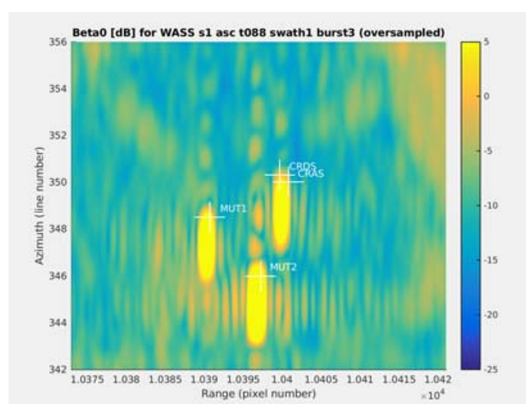
OVERSAMPLED BETA0 IMAGES FROM TSX AND S1



TSX ascending track 025



Sentinel-1 ascending track 088

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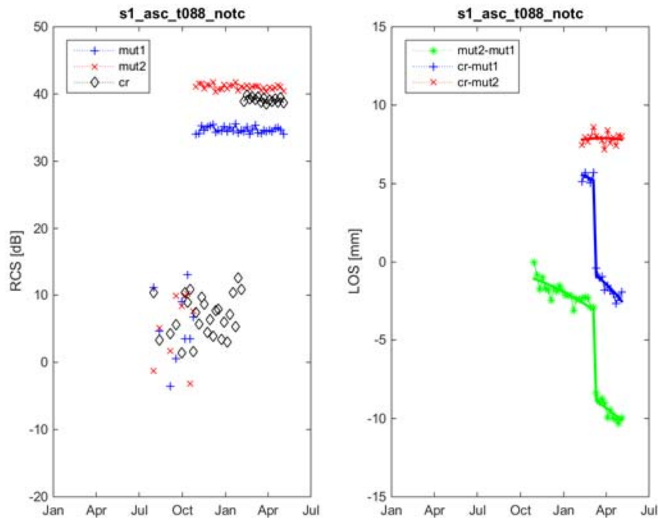
EXAMPLE RESULTS (S1 ASCENDING T088)



Deliberative shift in MUTE-1 of 7 mm in vertical

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RESULTS MUTE PROJECT

- Average RCS values MUTEs:

Average RCS [dBm2]	MUTE-1	MUTE-2
S1	34.3	39.9
TSX	29.7	30.5

- RMS error RCS MUTE’s 0.4-0.8 dBm2
- Excellent short term phase stability

  After fitting 2nd degree polynomial:
  - 0.3-0.7 mm rms for S1
  - 0.2-0.4 mm rms for TSX
- Non-linear trends in phase data possibly related to
  - Motion of the pole
  - Temperature correction (under investigation)

- Deliberative vertical 7 mm shift of MUTE-1 recovered within 50% reliability interval for 11 out of 12 combinations (1 within 95% reliability)

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INTEGRATED GEODETIC REFERENCE STATION (IGRS)

- Collocation and integration of seven independent geodetic techniques: the devices combines
  (i) a GNSS antenna and receiver,
  (ii) double back-flip radar reflectors for ascending and descending orbits,
  (iii) an airborne laser scanning target and (iv) a photogrammetric benchmark,
  (v) a triangulation benchmark, (vi) a leveling benchmark, and (vii) a relative gravity benchmark.
  A single mechanical construction is used.
- The main application is to solve the problem of datum connection in the observation space.
- Ideally suited for use at new installations.
- Deployment of 29 operational stations in the Groningen area, Netherlands.

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IGRS PROTOTYPES @ WASSENAAR TEST SITE

DBF90T-GNSS

DBF90X-GNSS

- Double BackFlip (DBF) Corner Reflector
- Inner leg 90 cm
- Nominal RCS 28.5 dBm2
- Position of GNSS antenna has been determined through a number of test
- Very rigid construction
- Model with extended plates has 7 dBm2 additional RCS

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DBF90T-GNSS AND DBF90X-GNSS RESULTS

	DBF90T			DBF90X		
Track	Mean RCS [dBm2]	Std RCS [dBm2]	Std DD phase [mm]	Mean RCS [dBm2]	Std RCS [dBm2]	Std DD phase [mm]
s1_dsc_t110_swath2_burst4	28.89	0.59	0.33	35.74	0.31	0.64
s1_dsc_t037_swath3_burst3	28.66	0.56	0.09	35.14	0.30	0.17
s1_asc_t161_swath3_burst3	28.87	0.42	0.39	35.34	0.12	0.45
s1_asc_t088_swath1_burst3	27.80	0.83	0.29	35.56	0.09	0.34
average	28.55	0.60	0.28	35.44	0.21	0.40

Standard deviation in DD phase is 0.3-0.4 mm in equivalent line-of-sight.

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IGRS BORGSWEER GRONINGEN (NAM)

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ECR EXPERIMENT IN WASSENAAR

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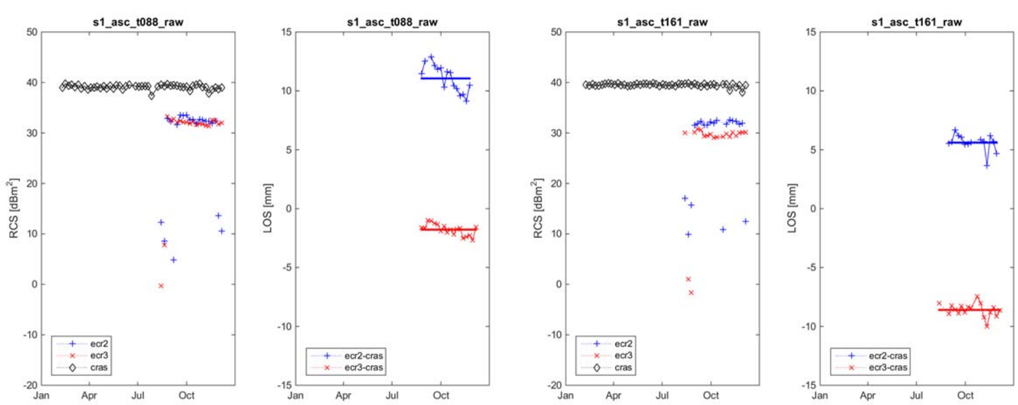
ECR RESULTS ASCENDING TRACKS



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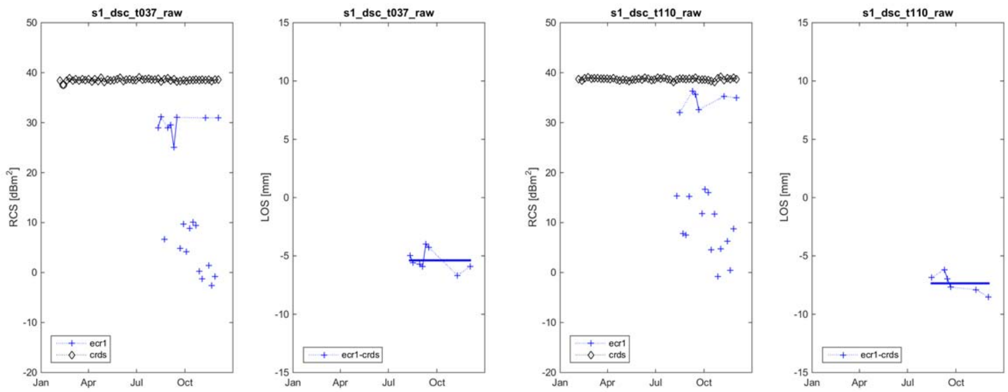
ECR RESULTS DESCENDING TRACKS



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ECR RESULTS

Table 1. Incidence and off boresight angles for various Sentinel-1 tracks (antenna boresight angle is 38 degrees.)

		Incidence angle [deg]	Off boresight [deg]	Mean RCS [dBm²]	Std RCS [dBm²]	Std DD phase mm
ECR1	dsc t110 swath2 burst4	36.68	−1.32	34.5	1.74	0.84
	dsc t037 swath3 burst3	44.64	6.64	29.6	2.05	0.91
ECR2	asc t161 swath3 burst3	41.77	3.77	32.0	0.39	0.73
	asc t088 swath1 burst3	33.23	−4.77	32.6	0.59	1.15
ECR3	asc t161 swath3 burst3	41.77	3.77	29.8	0.50	0.58
	asc t088 swath1 burst3	33.23	−4.77	32.1	0.49	0.48

- RCS comparable to 1.03 m triangular corner reflector
- Phase precision is in the order of an equivalent displacement of 0.5 mm.

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DATA FORMATS

- Data exchange format
- Station log

This is a work in progress, but standardization seems to be a logical next step, and one where EUREF could play a role.

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THANK YOU FOR YOUR ATTENTION

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