Mexican Collaborations - Projects XPLORE, XIBALBA, and XIB_TCS

Extended Karst Studies with Innovative Methods in Area of Tulum/Mexico

Aerogeophysics – hydr. Modeling – 3d Laserscanning – Laser Flux Imaging – TCS-Monitoring

Amigos de Sian Ka'an

Geological Survey of Austria

Arnulf Schiller

Université de Neuchâtel · FWF · ÖAW · FNSNF Schweizerischer Nationalfonds zur Förderung der wissenschaftlichen Forschung

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History of 10 Years Austrian-Mexican Cooperation in Tulum

2006: Pilot ground surveys in the Tulum karst system: ERT, EM.
2007: First aerogeophysical survey and ground measurements.
2008: Second aerogeophysical survey and ground measurements.

2008 - 2012: Project Xplore

Goals: Acquisition and advanced processing of geophysical data for input of innovative hydro-geological modeling (UNINE) / advanced imaging of the karst conduit system with AEM-data.

2009: Aerogeophysics near Cancun and Chetumal, Socorro, extended ERT in Tulum.
2010: Large ground geophysical campaign (ERT, GPR, borehole geophysics,
set up of GWL logger network, water analysis on site and in laboratory).

2011: High precision GPS GWL survey, retrievement of GWL/halocline loggers, water analysis.
2012: High precision GPS GWL survey with inland tides observation, water analysis.

2012 – 2017: Project Xibalba

Goal: Medium/Small scale acquisition of hydrogeological parameters with innovative Methods (conduit geometry laser scanning, laser flux imaging) directly in the conduits, ERT, extended GWL observation, tracer tests. Refining hydrological model (UNINE).

Starting 2016: Project Xib_TCS: Citizen supported ground water monitoring network.

Partners

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Speleotech
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CONANP

Project Funding

The Nature Conservancy, Unesco (AEM Surveys Tulum 2008/2009)

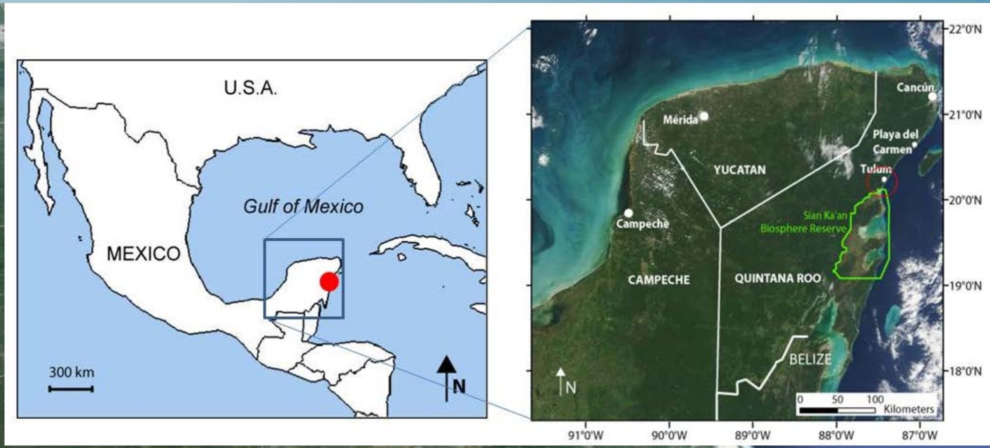
Austrian Science Fund (projects HIRISK, Xplore, Xibalba, Xib_TCS)

Austrian Academy of Sciences (programme ‚Man and Biosphere')

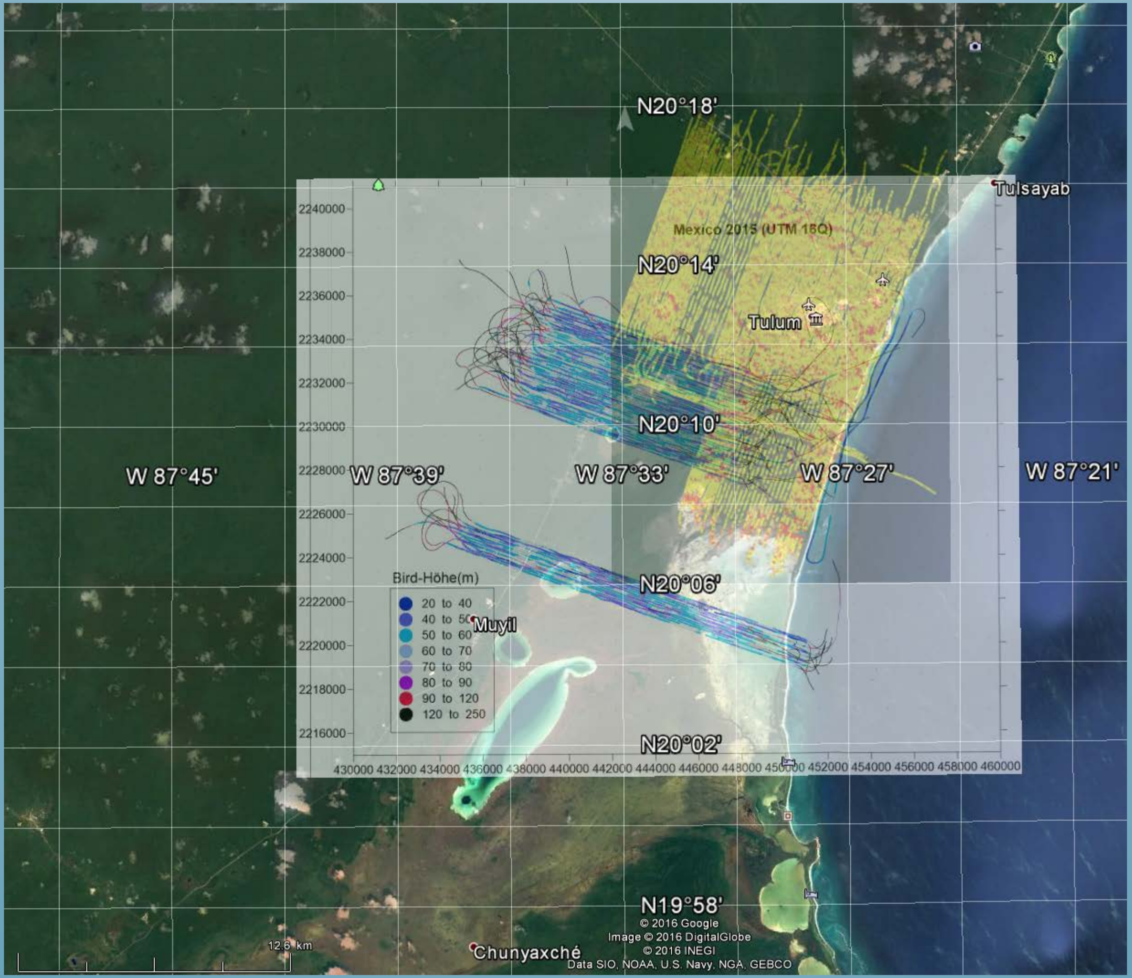
Swiss Science Fund (project Xibalba)

The Survey Area – Tulum Karst Plain

- huge and difficult accessible coastal karst plain covered with forests, mangroves and lagoons
- variably consolidated limestones several 1000 metres thick.
- thin soil cover – limestone exposed at the surface
- flat topography (0 - ~50 m above mean sea level)
- known conduits/caves explored by cave divers
- freshwater layer above saltwater body
- tidal variation of groundwater and halocline level reaching inland
- socio-economic impact due to urban development and increasing water demand
- climate change



AEM Surveys Tulum 2007, 2008 and 2015: approx. 250 km²



Project XPLORE – Problem Statement and Methodology

- Can **AEM** map the underground conduit system?
- Can a Karst water regime be described by **combining aerogeophysical** and **hydrogeological** methods?

Methodology:

Pilot surveys, simulation of measurement situation – estimation of expected measurement signal

AEM-Survey → ***electrical conductivity** in the subsurface (through 1D-inversion)*

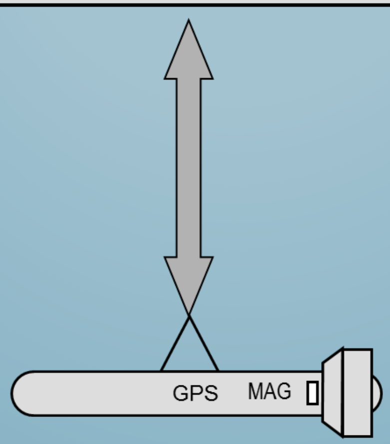
El. Conductivity → *lateral and vertical distribution of **hydrogeological relevant structures** (due to distribution of porosity, water saturation, ion concentration, permeability, GWL, halocline) – Map of potential conduits.*

Structural information from AEM and under water cave surveys → ***Groundwater model***

***Calibration** of AEM-measurements and groundwater model by ground survey data (ERT, bore hole geophysics, piezometry, GPR)*

The measurement platform

data monitoring and recording
DOS (WINDOWS NT 4.0*)



laser-altimeter – RIEGL

GPS navigation – 2*TRIMBLE 2000
(GLONASS ASHTECH*)

infrared sensor (8-13mm) - RAYTEK

video camera (flightpath recorder)

gammaray spectrometry -
PICODAS PGAM-1000
1 NaJ crystal mit 4.2 l "UP"
8 NaJ crytals mit 33.6 l "DOWN"

AIRBORNE SENSOR - HUMMINGBIRD

4 frequency electromagnetic system

f_1= 340 Hz horizontal coplanar loops
f_2= 3200 Hz vertical coaxial loops
f_3= 7190 Hz horizontal coplanar loops
f_4= 28850 Hz vertikal koaxial loops

Cesiumtype magnetometer Scintrex CS-2

The Austrian Airborne System

Helicopter provided by the Mexican Marina (MilMi - 8)

Survey area as seen from helicopter

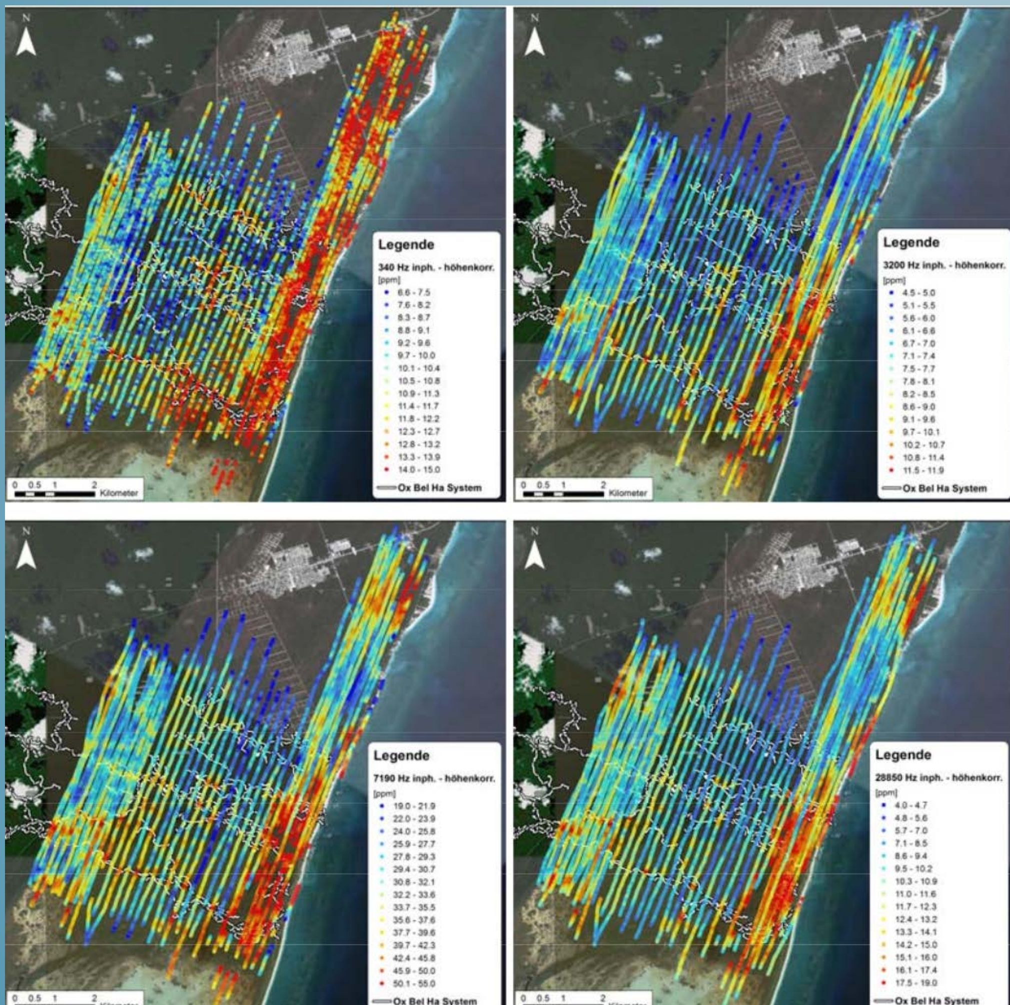
load specialist

Bird 30 m below the helicopter

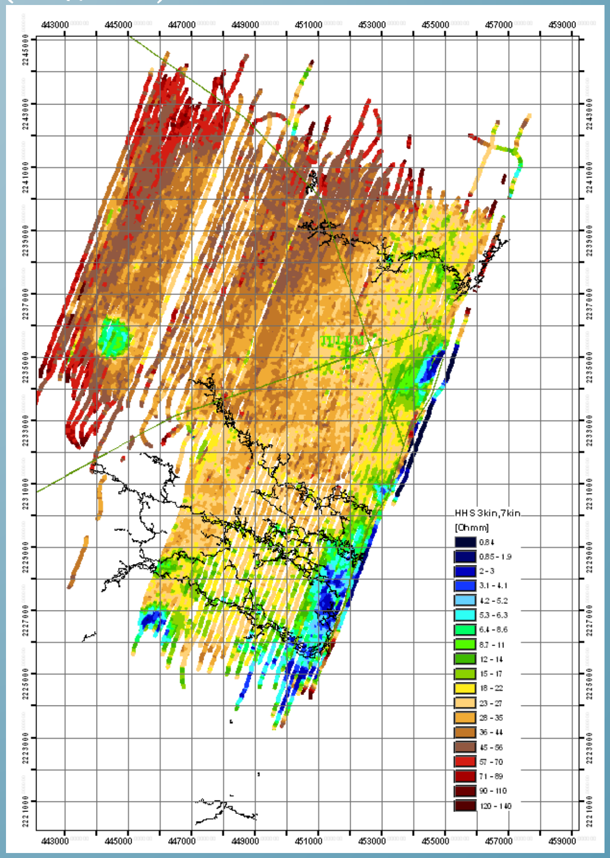
The 2007/2008 AEM surveys –first results

known caves are detected – some indication of further conduits

Edited and height reduced raw signal (ppm) of all inphase components (2007)

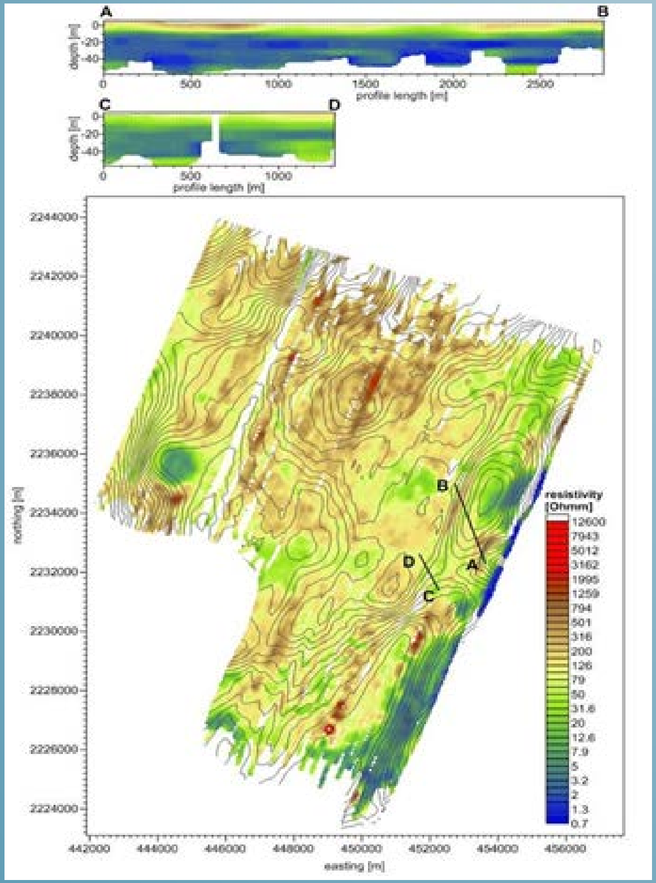


Halfspace inversion from 3k_in, 7k_in – phases (2007/2008)



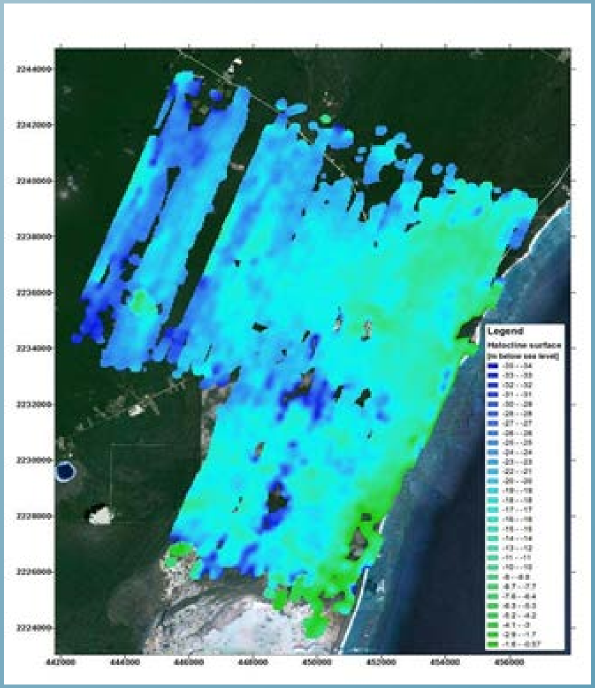
AEM-data inversion

surface layer and two sections
(software: UBC EM1DFM)



Estimated topography of halocline

(Interpreted as
4 S/m – isosurface)



Getting out more information - adapting AEM processing for enhancing signals of possible conduits

1) System drift analysis (HIRISK)

2) Automatic drift correction
based upon findings/developments of
FWF project HIRISK.

3) Estimation and correction of residual drift by
analysis of vertical field gradient.

4) Destripping (type of micro-levelling).

6) Advanced reduction of active interferences
(median/phase filtering, in development)

2007/2008 f3_in , reduced to 40
meters above ground, meanfree.

System drift analysis (FWF - project HIRISK)

The Problem

The system is (as any comparable system) generating non linear drifting of in/out- phase components due to following sources:

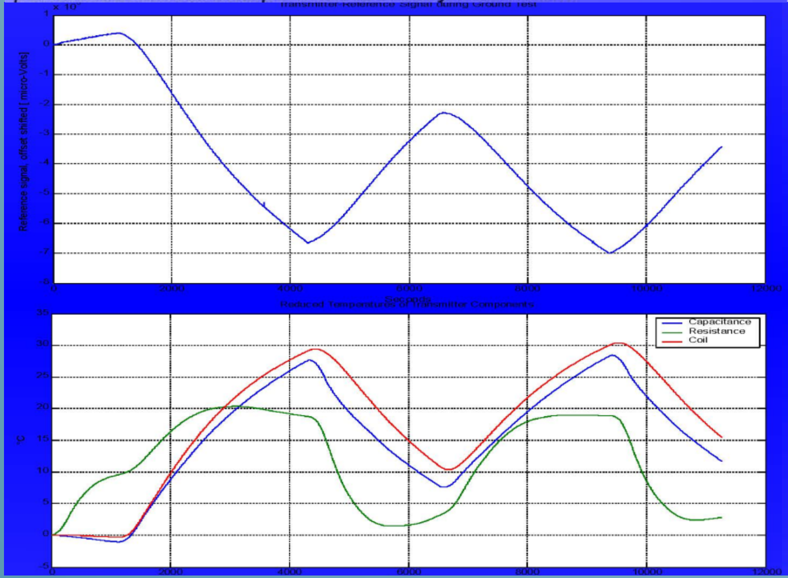
- D/A conversion of synthetic signal
- Transmitter amplifier
- Transmitter circuits
- Suboptimum impedance matching
- Variable Tx/Rx - coil geometry
- Receiver circuits
- Suboptimum Rx/Bx primary field compensation
- Receiver pre-amplifier
- Receiver A/D conversion
- Parasitic secondary fields originating from hardware, wiring etc.

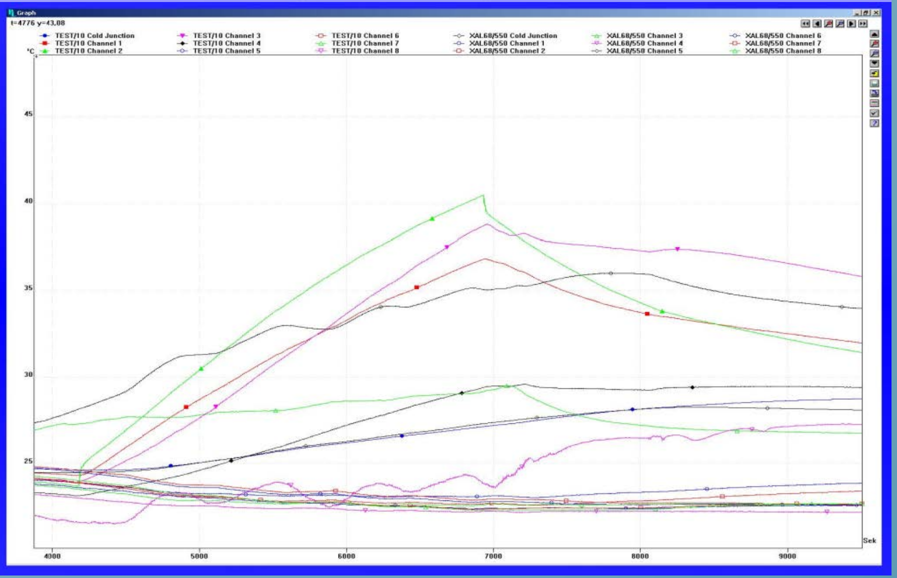
!All these sources are highly temperature sensitive. As temperature (environmental or self generated) changes continuously with time, nulling,phasing and Q-coil calibration is valid only for the time performed! Linear interpolation is mostly insufficient.

Identified main drift sources:

- Temperature induced changes in Tx/Rx circuit parameters => detuning, suboptimal impedance matching, suboptimal bucking compensation, temperature sensitivity of analogous hardware (anti-aliasing-filter, amplifier)
- Residual drift originating from system immanent secondary fields (hardware, wiring) => difficult to simulate accurately.

- Modeling of contributions by least squares fitting which attempts to solve a system of linear equations A*x=b for x if A is consistent, otherwise it attempts to solve the least squares solution x that minimizes norm(b - A*x). In this case 'b' represents the drifting data, 'A' the temperature dependent transfer-functions calculated with measured component temperature and x represents the contributions as well as the higher order temperature co-efficients.





Automatic signal drift correction by means of transmitter drift correction and drift estimation (result: blue line)

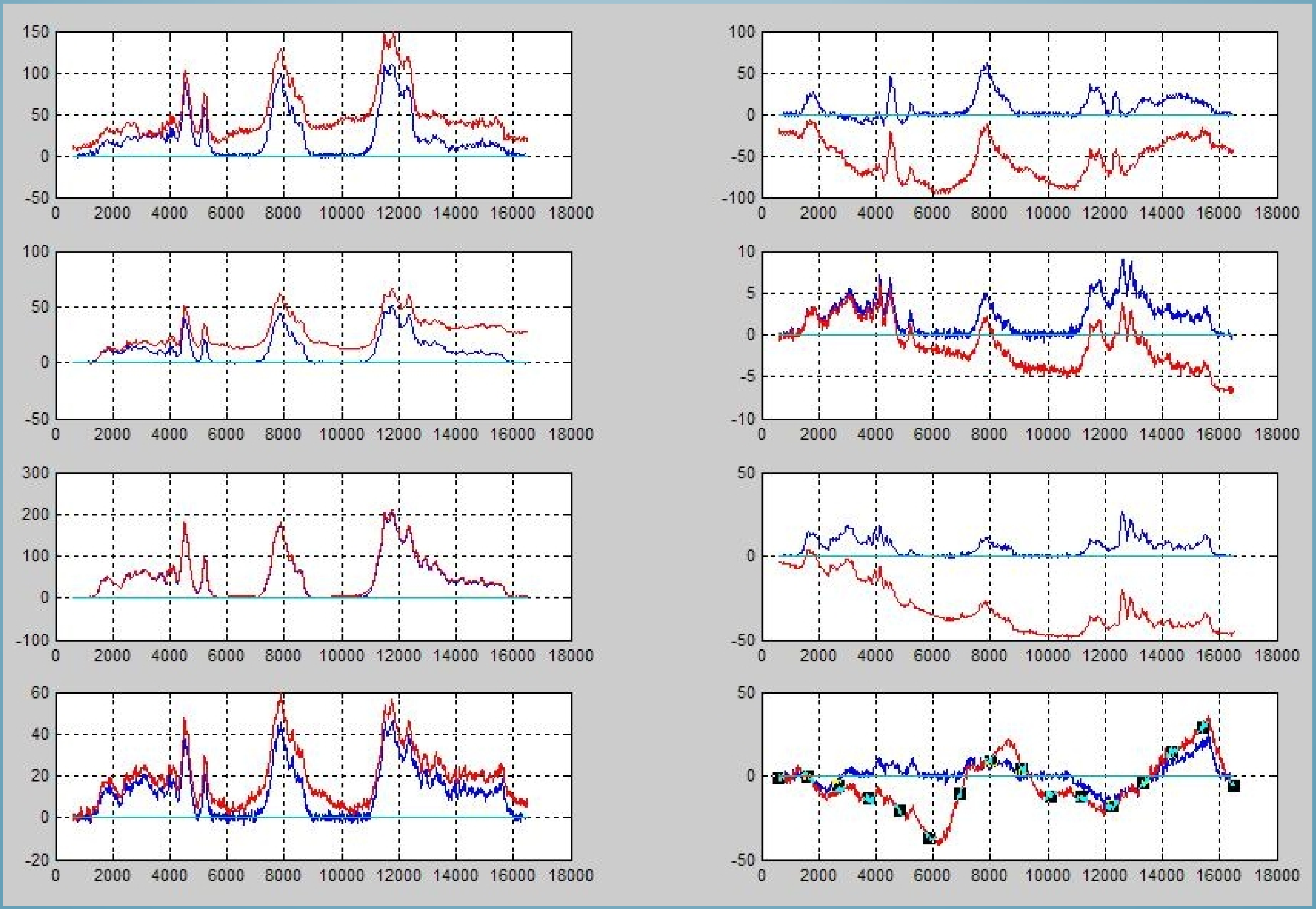
in-phase (ppm) quadrature (ppm)

340 Hz

3200 Hz

7190 Hz

2850 Hz



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Residual system drift estimation by analysis of signal/height correlation

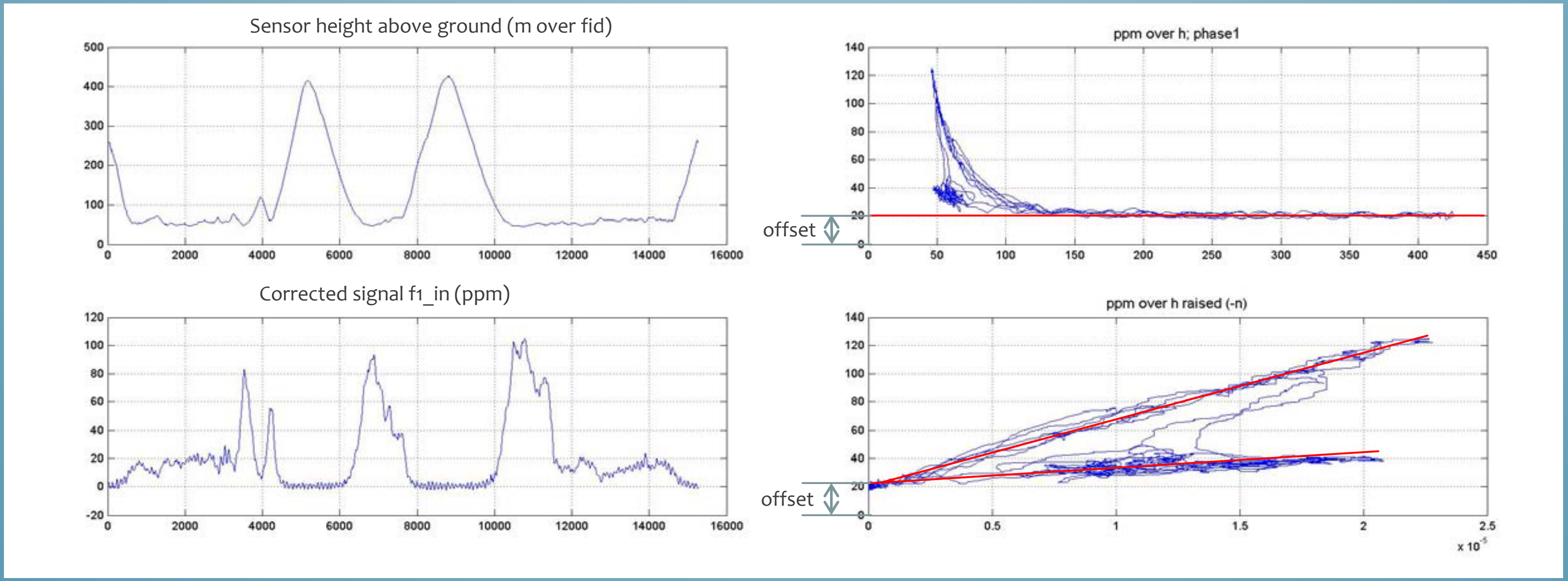
Extrapolation of signal to h -> ∞ (synthetic nulling during measurement) by fitting a model to data within gliding window. Controlled by quality criterion (standard deviation of fit). Works best above more homogenious layering .

$$s = q \times h^{-n} + d$$

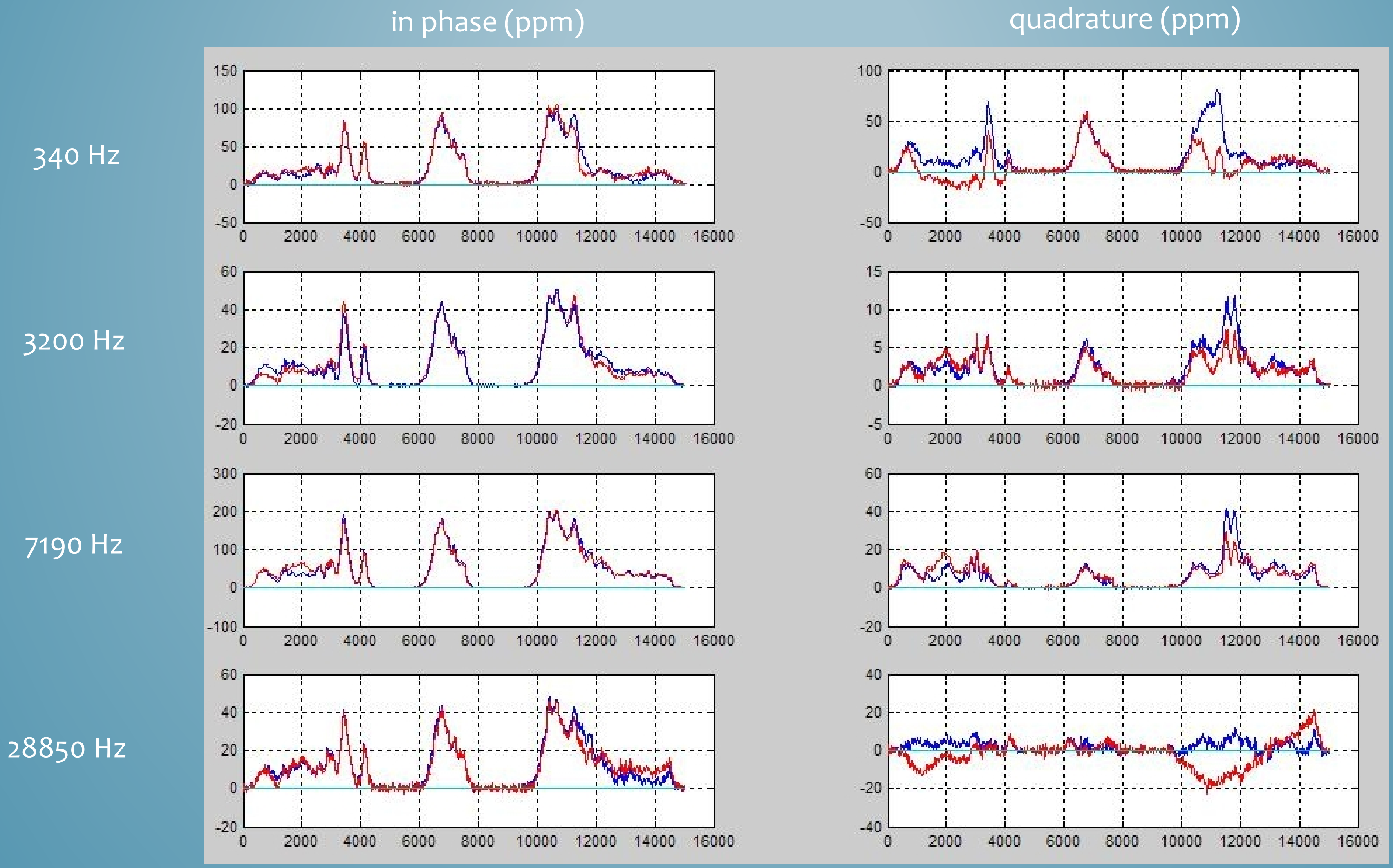
$$s = q \times (h + t)^{-n} + d$$

s … signal
q … source strength
h … laser sensor height
n … decay exponent (3)
d … drift offset

Line YUK003, 2008-survey

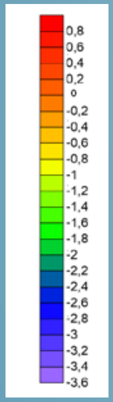


Residual signal offset correction due to signal / altitude relation (result: blue line)

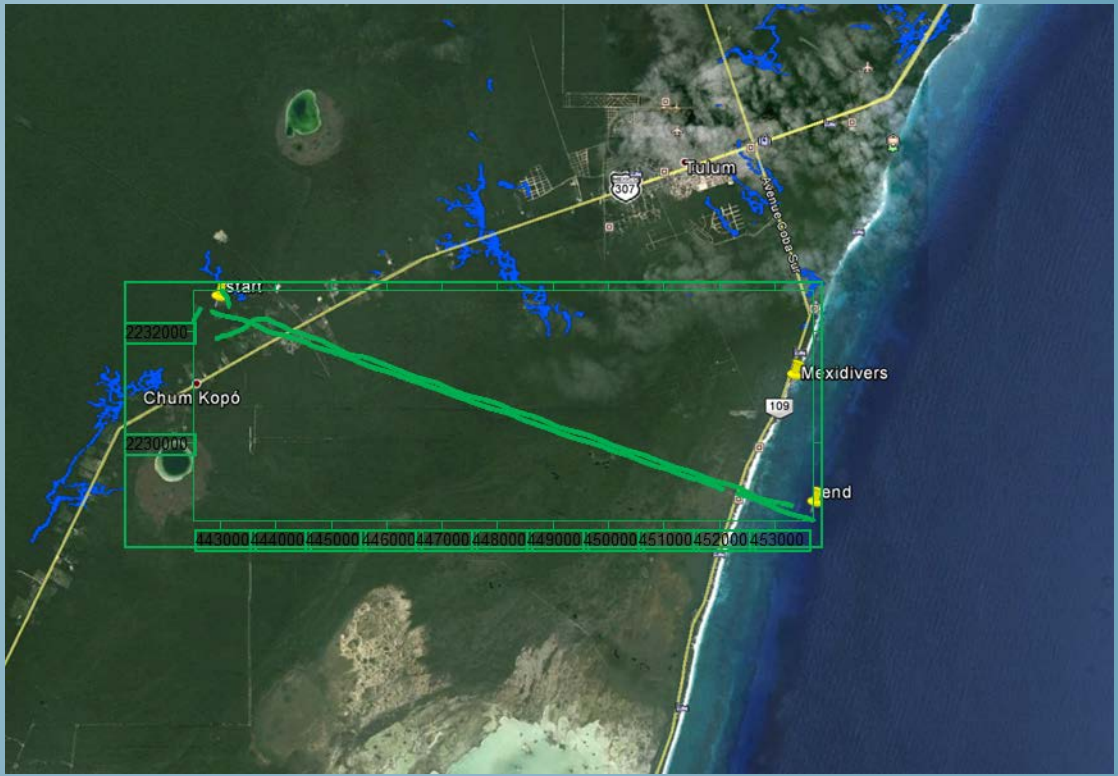


Sections beneath flight lines:

Detection of fresh water layer, mixture zone and salt water body



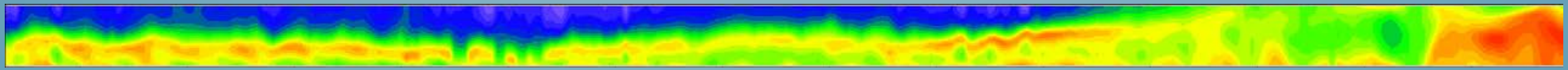
Electrical Conductivity Log10[S/m]

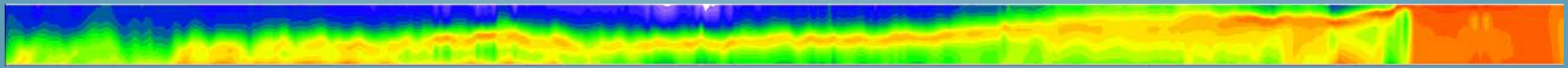


Line YUK001, 2008-survey

Fresh water layer (blue) ~ 10 km Low wet land reef

50 m depth

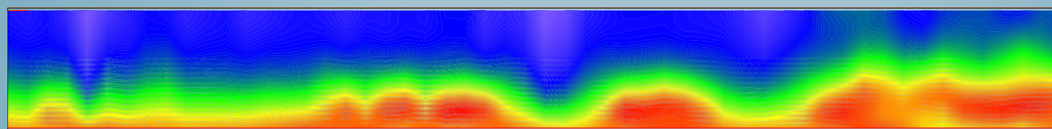




Salt water body (yellow-red)

Where are the caves? – background reduction of strong salt water response in line-inversion results.

YUL054_detail



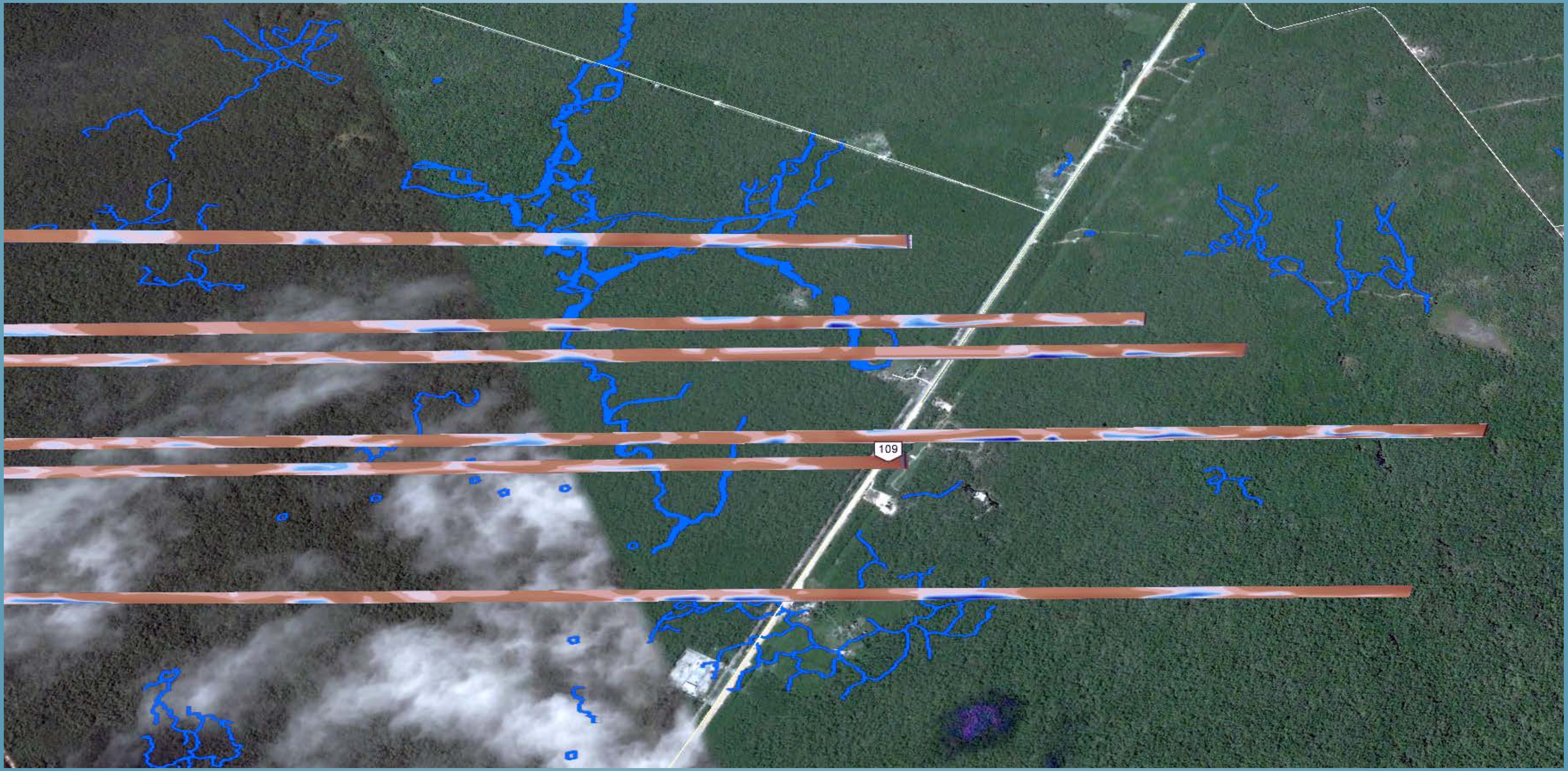
minus

log_{10}[s/m]

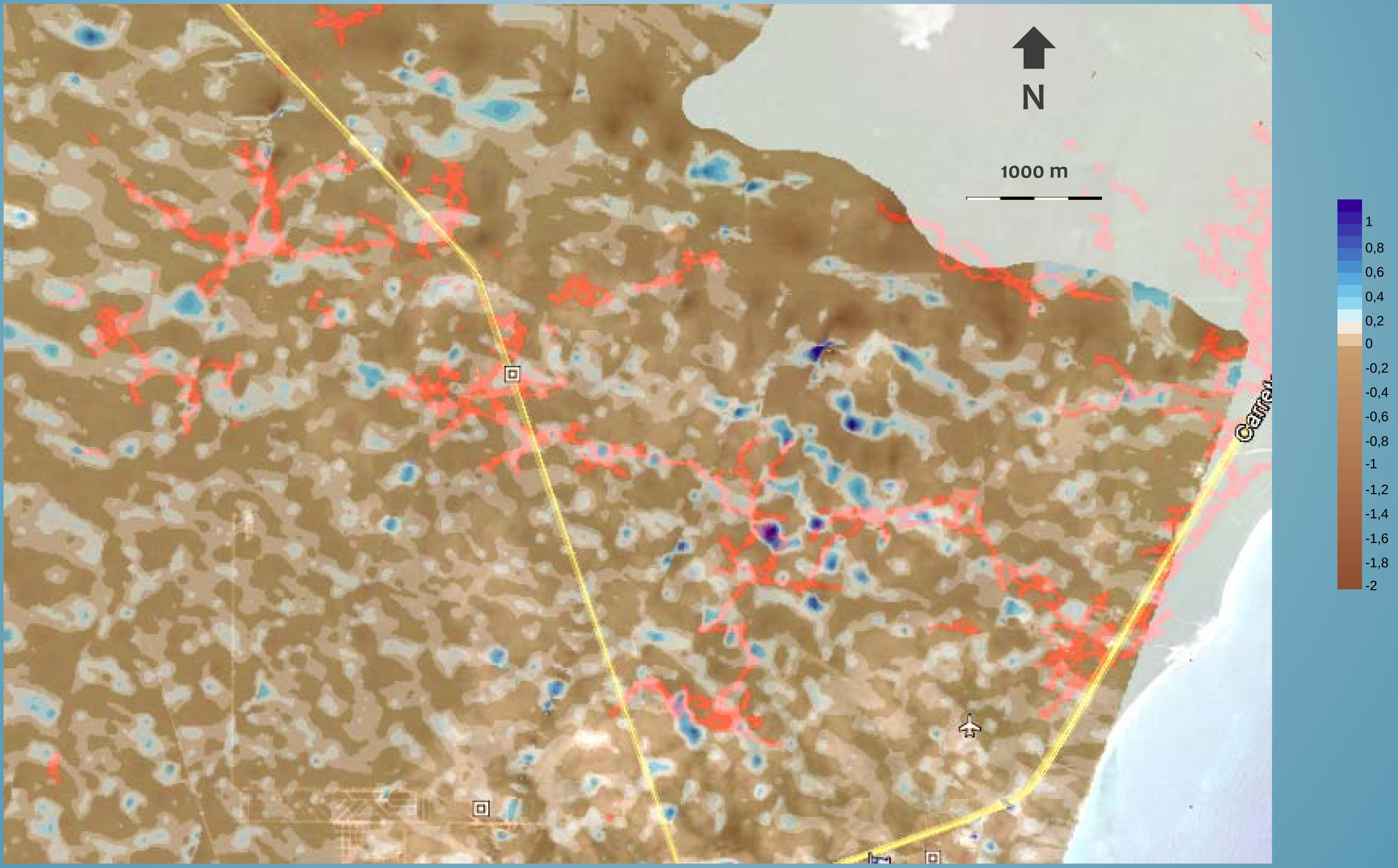
=

L1

Background reduced sections crossing surveyed cave system

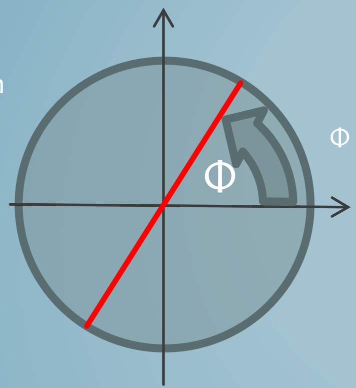


Background reduction– 19.5 metres depth layer - detail

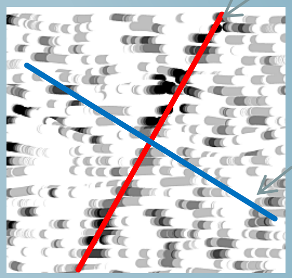


Advanced AEM processing – enhancement of linear structures

linear filter orientation



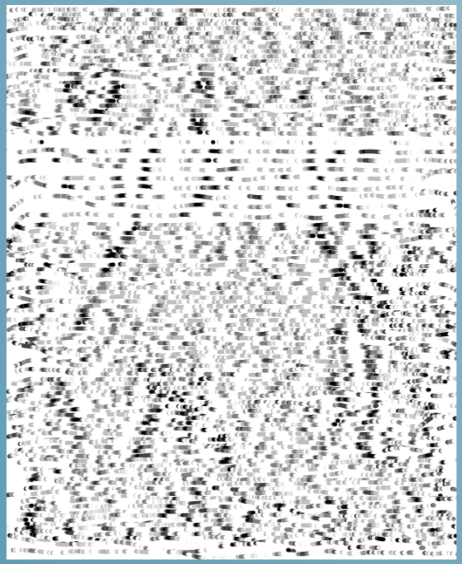
$\Phi = 0° - 180°$



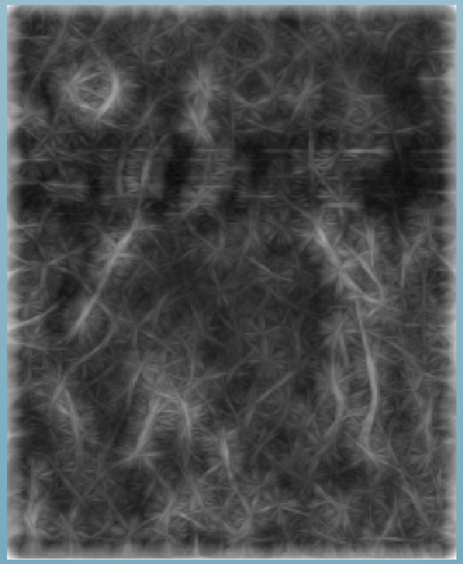
high filter output

low filter output

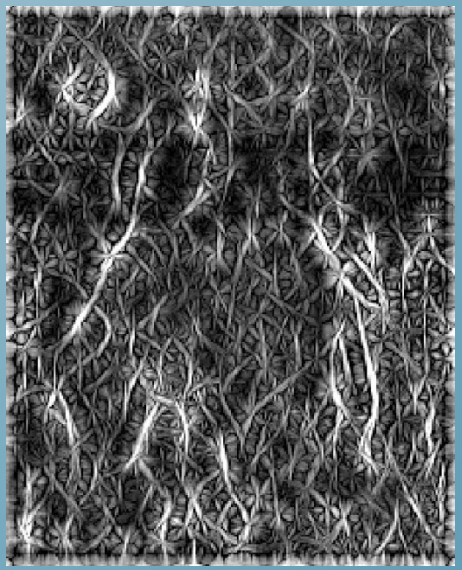
Height reduced and
mean free ppm-signal
(f3_in, part of 2008-survey)



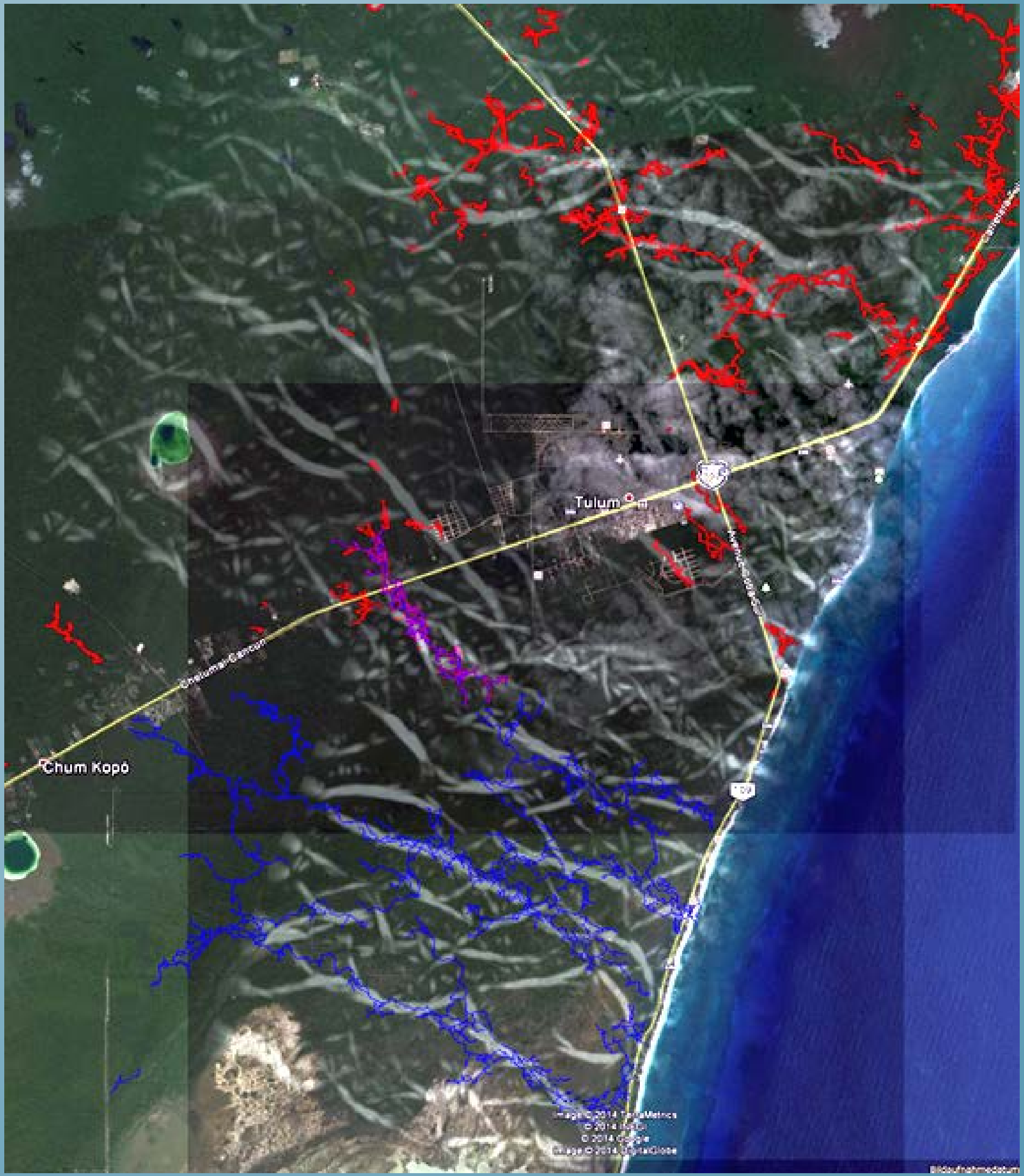
Linear structures enhanced



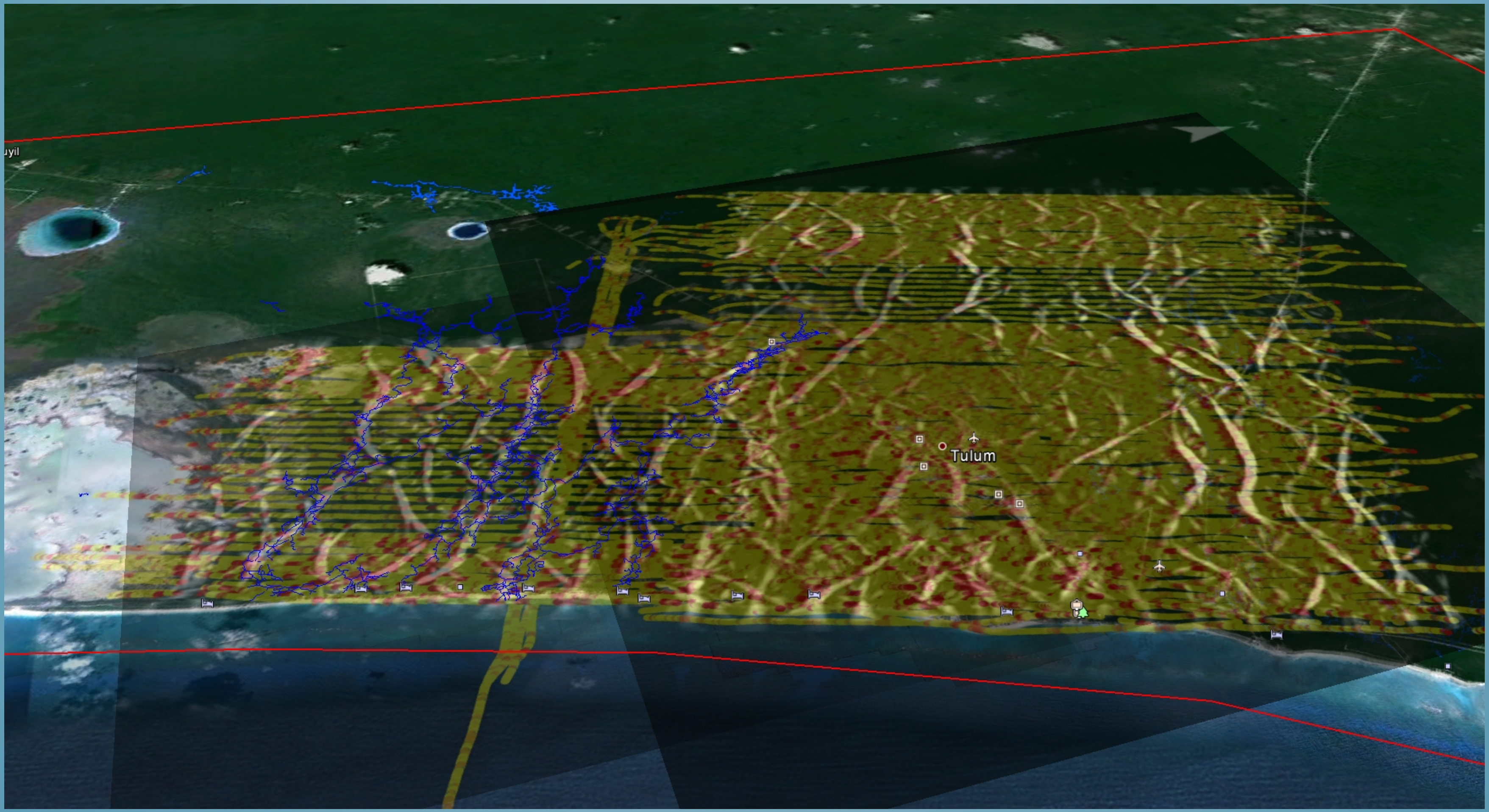
edge filtered



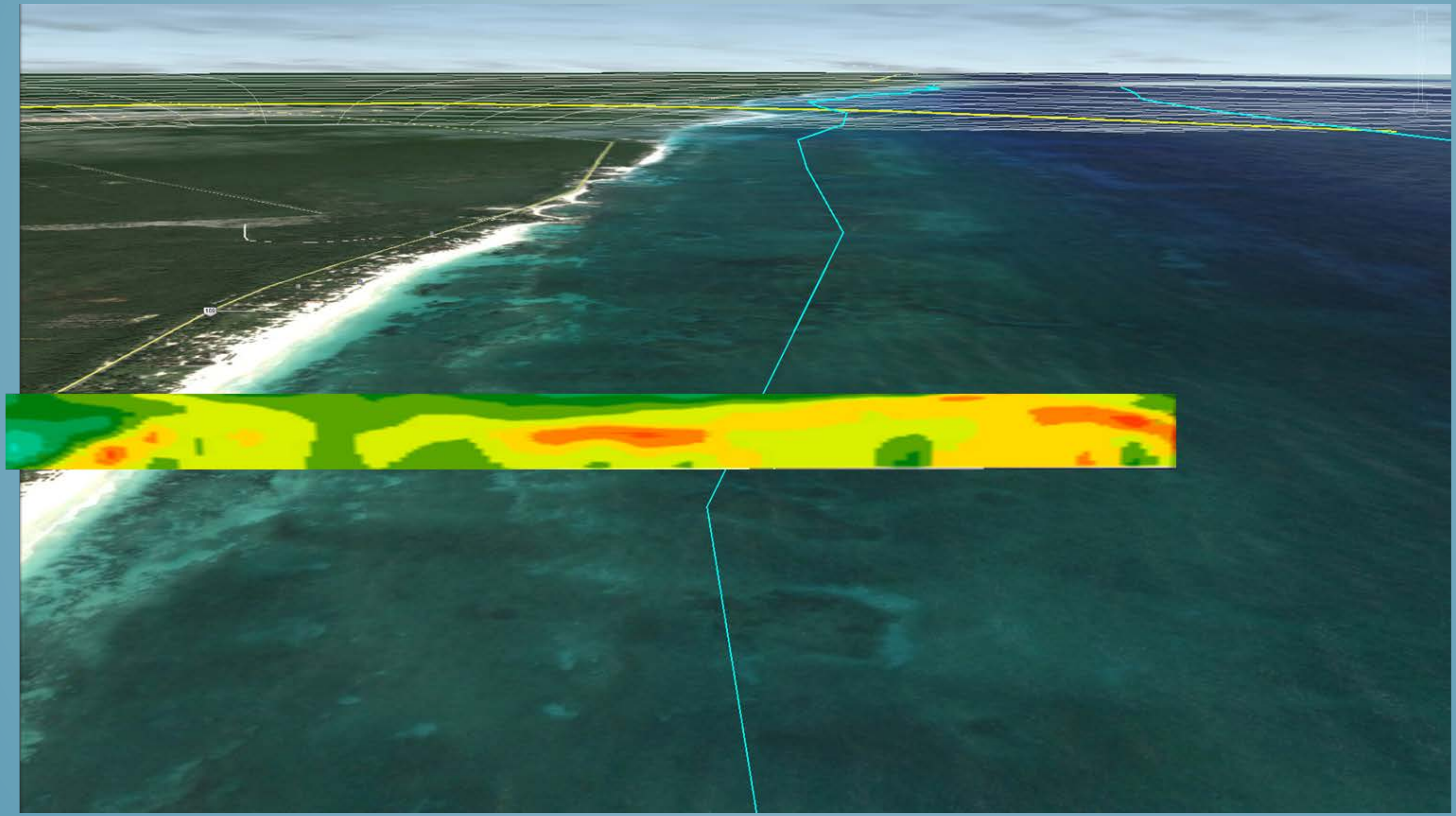
Map of enhanced linear structures compared with surveyed caves



Results: Overview of conduit network (from 2007 and 2008 AEM data)



Inversion line YUK001 – detailed section of reef structure



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Rancho Viejo
Tulsayab
Tulum
Chum Kopó
4.27 km
Image © 2016 DigitalGlobe
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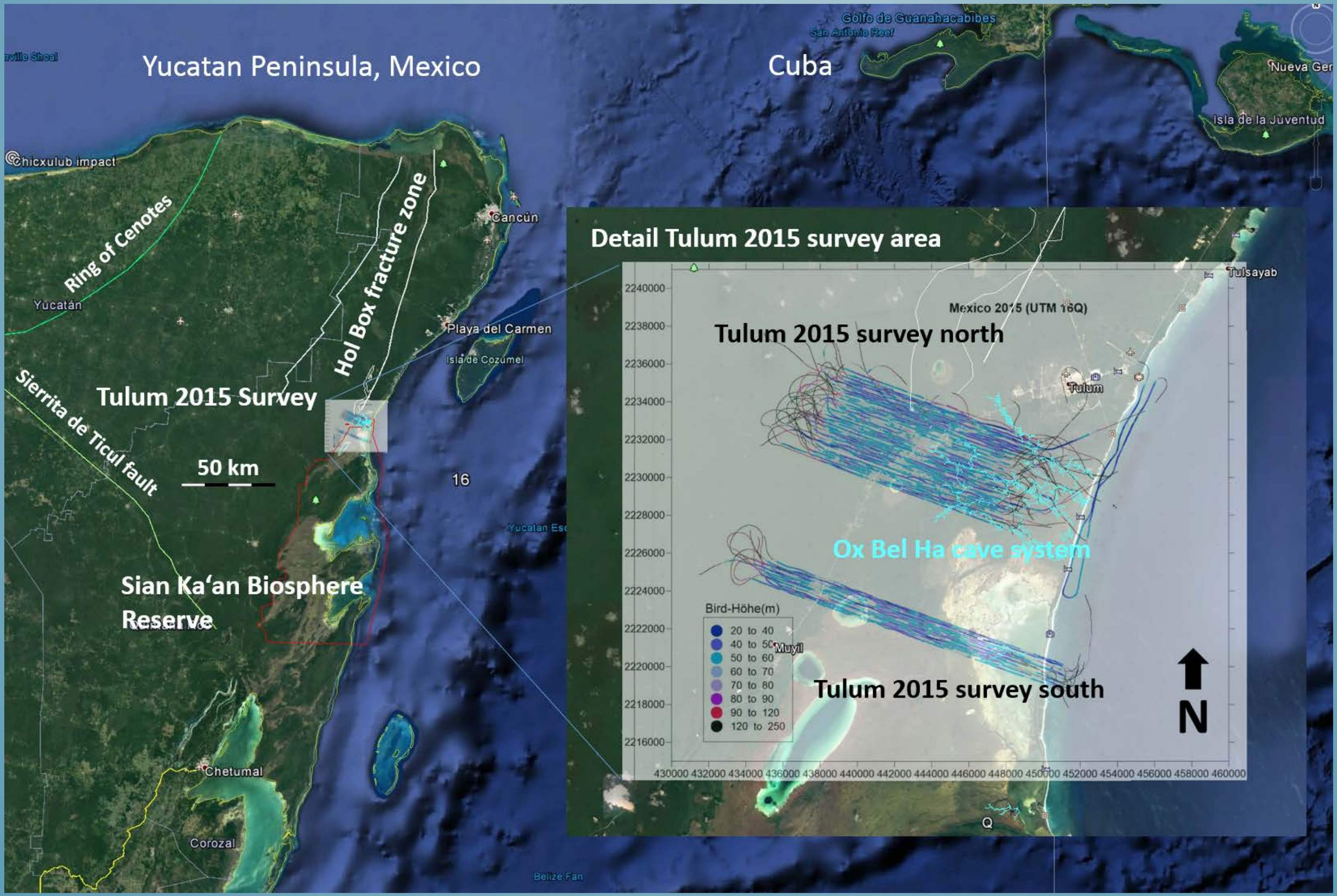
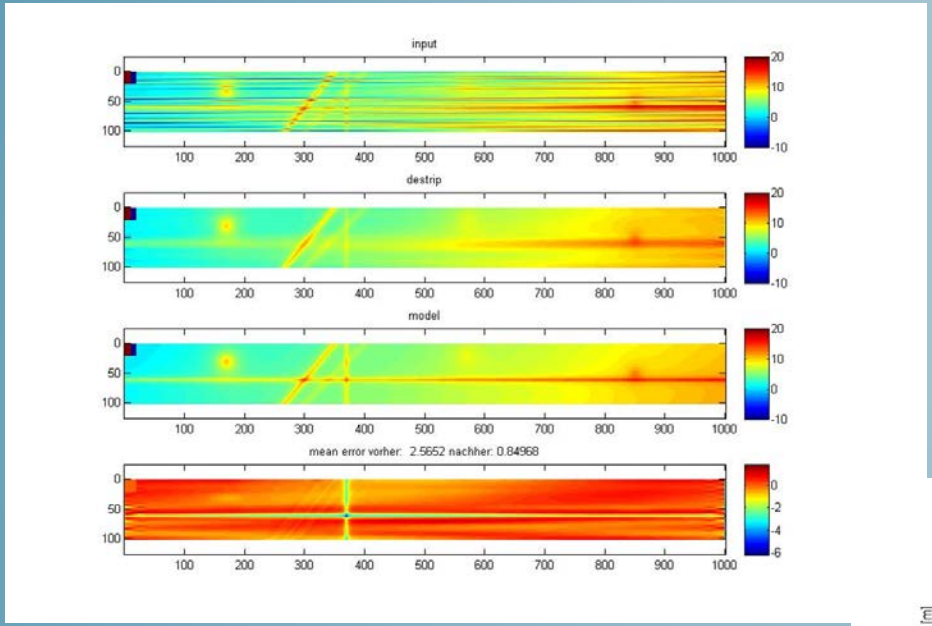
Image © 2016 TerraMetrics
© 2016 INEGI
Google Earth

Tulum 2015 AEM-Survey



Test of destripping scheme



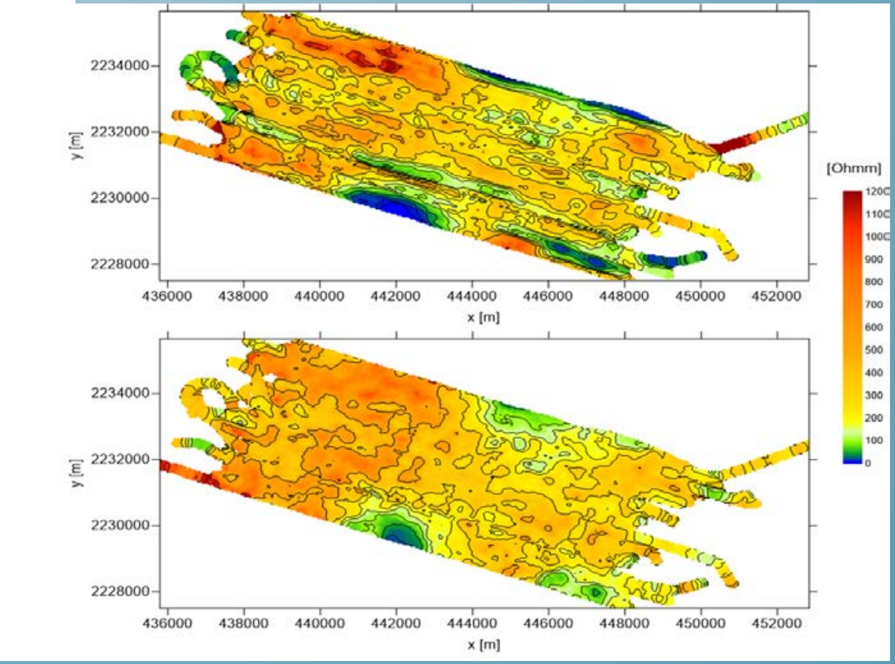
Strips caused by residual signal drift
- spatially uncorrelated normal to flight lines.

Estimation of spatial frequency content of system drift – low pass filtering

Iterative 3 point balancing.

Minimizing variability normal to lines by preserving anomalies along lines.

Top: synthetic test.



Right: AEM 2015 – north part.
Inversion result of upper layer (0-3 m).
top: inversion with residual drift.
bottom: inversion with destripped ppm data input.

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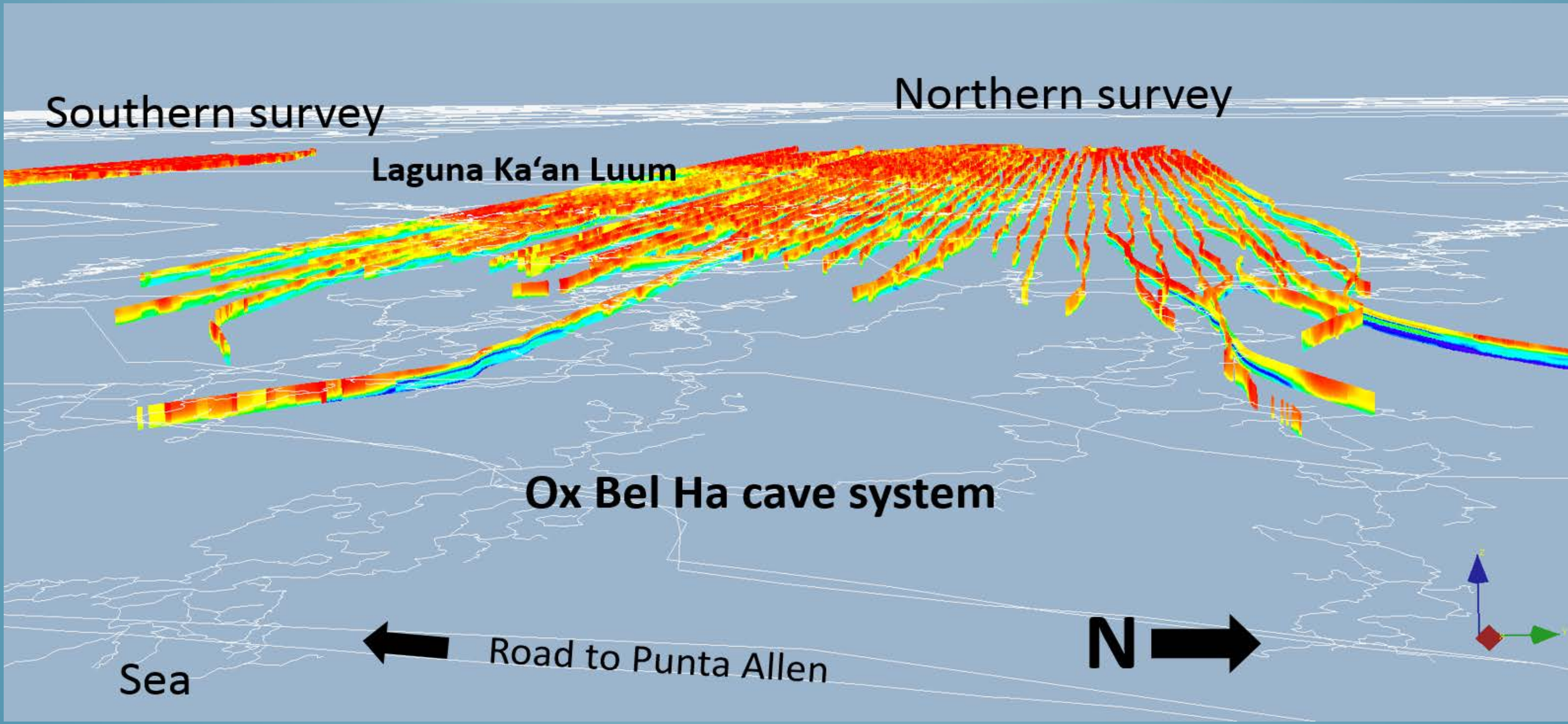
2015 AEM-survey inversion in 3d-representation



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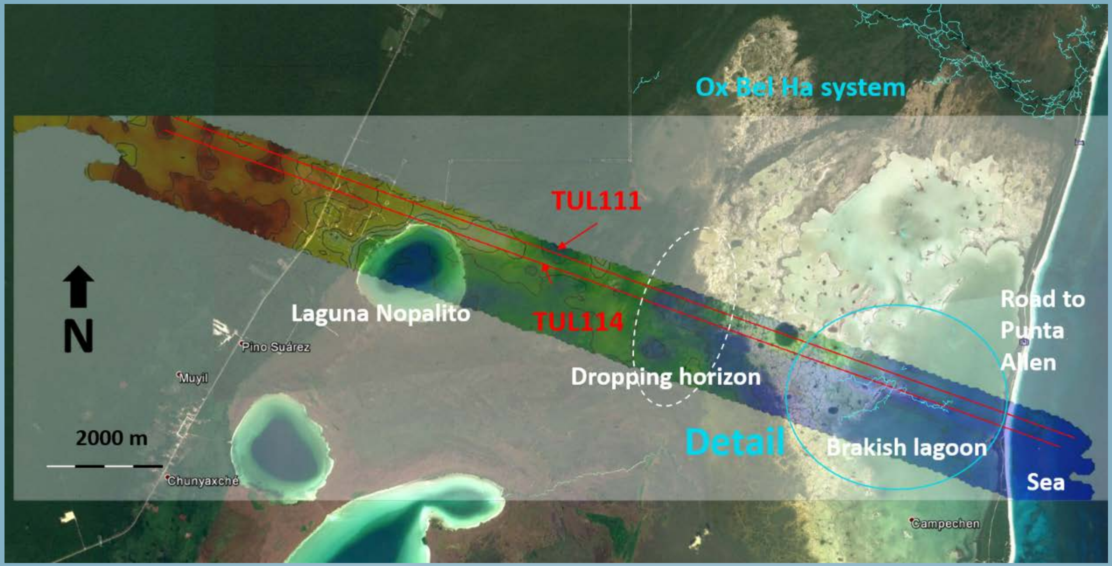
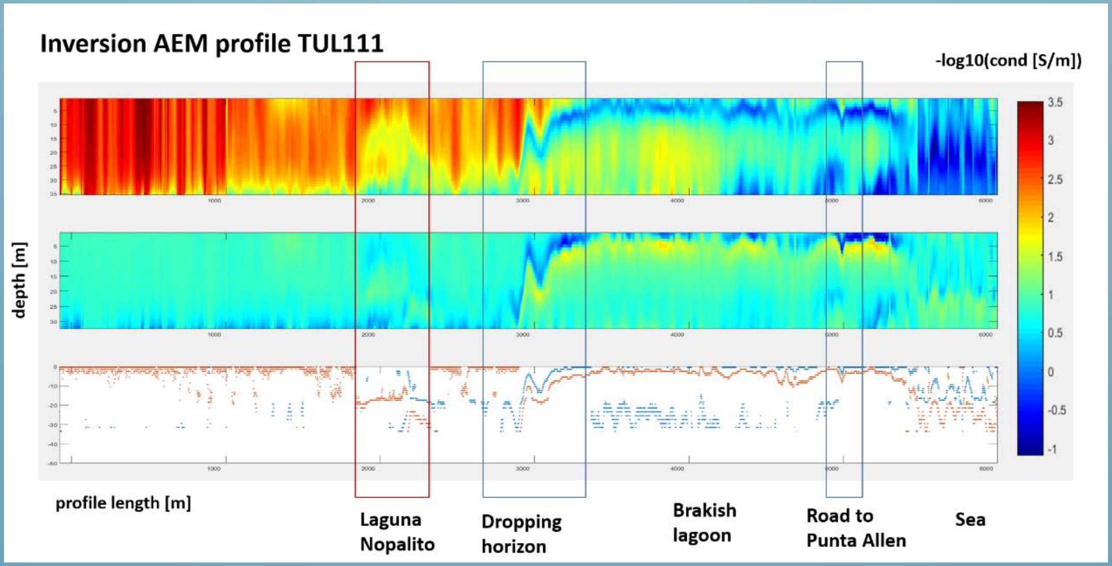
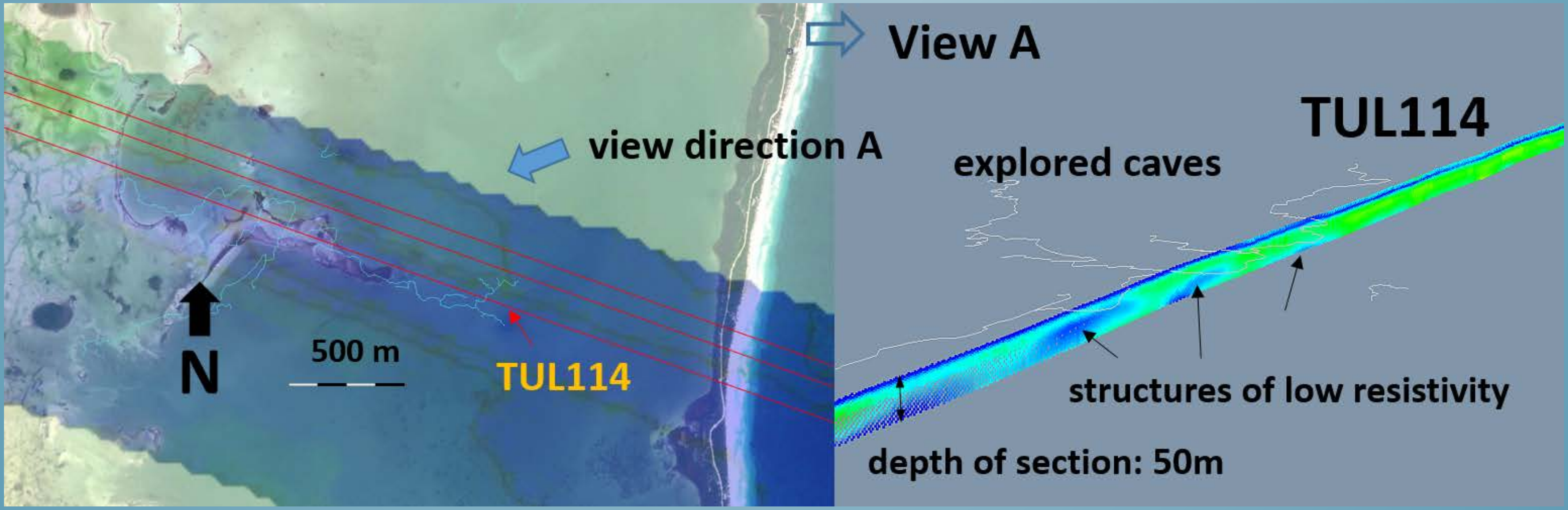
Results: vertical sections to 50 metres depth (from 2015 AEM data)

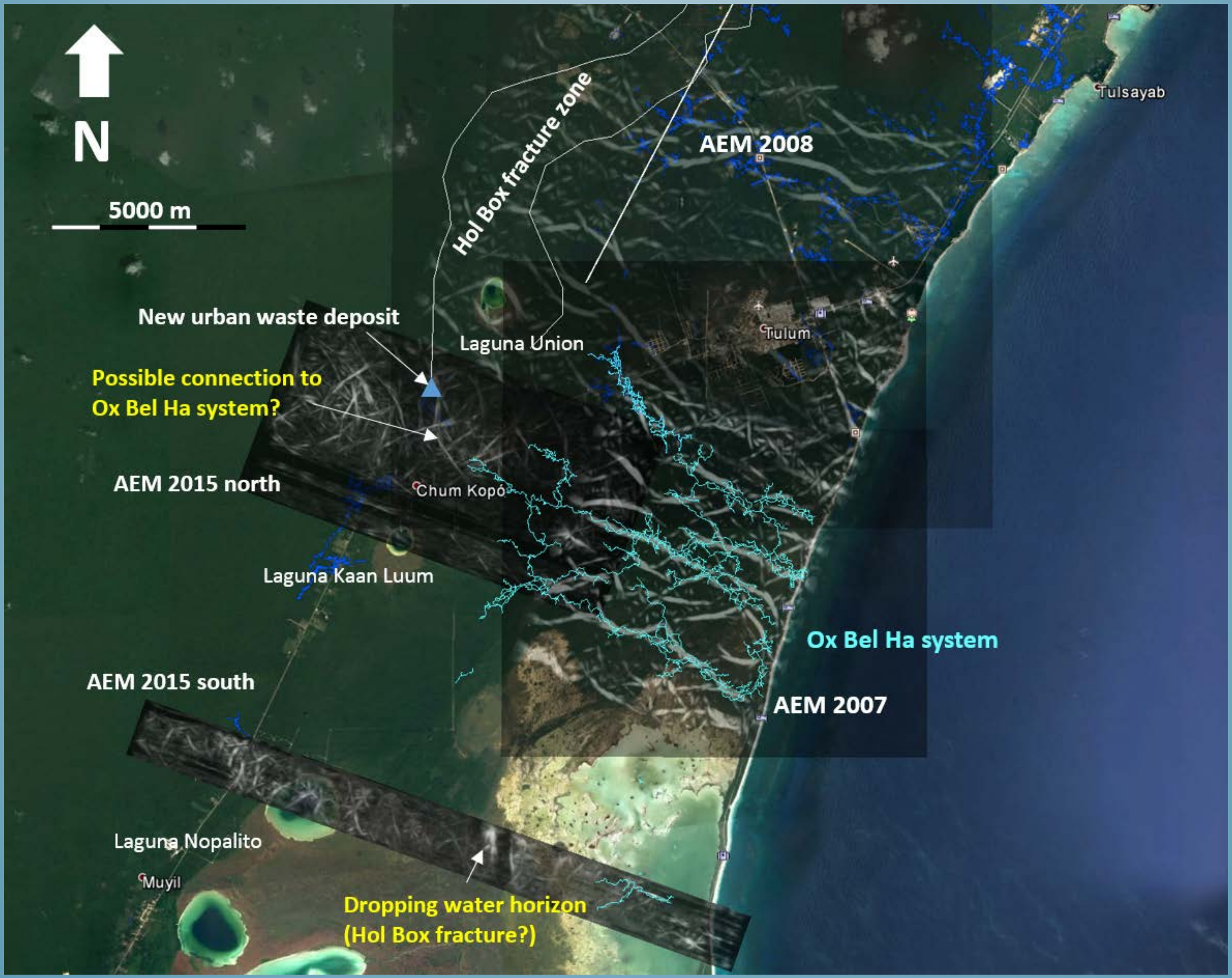




Detail of line TUL114. Right: perspectivic view to section cutting known caves



Combined conduit maps of 2007, 2008 and 2015 surveys



Conclusion of AEM survey in Tulum Karst:

- Halocline level is well resolved.

- GWL is not clearly resolved in karst (capillary effects). Interpretation with conductivity isosurface problematical (varying porosity).

- Distribution of electrical conductivity derived from AEM as XYZ-volume data correlates to surveyed caves and yields picture of potential karst conduit distribution - lateral and in depth.

- Lateral resolution approx. 50-100m (spacing dependent), maximum vertical resolution 2 m, maximum penetration depth approx. 50 metres in the case of salt water saturated limestone.

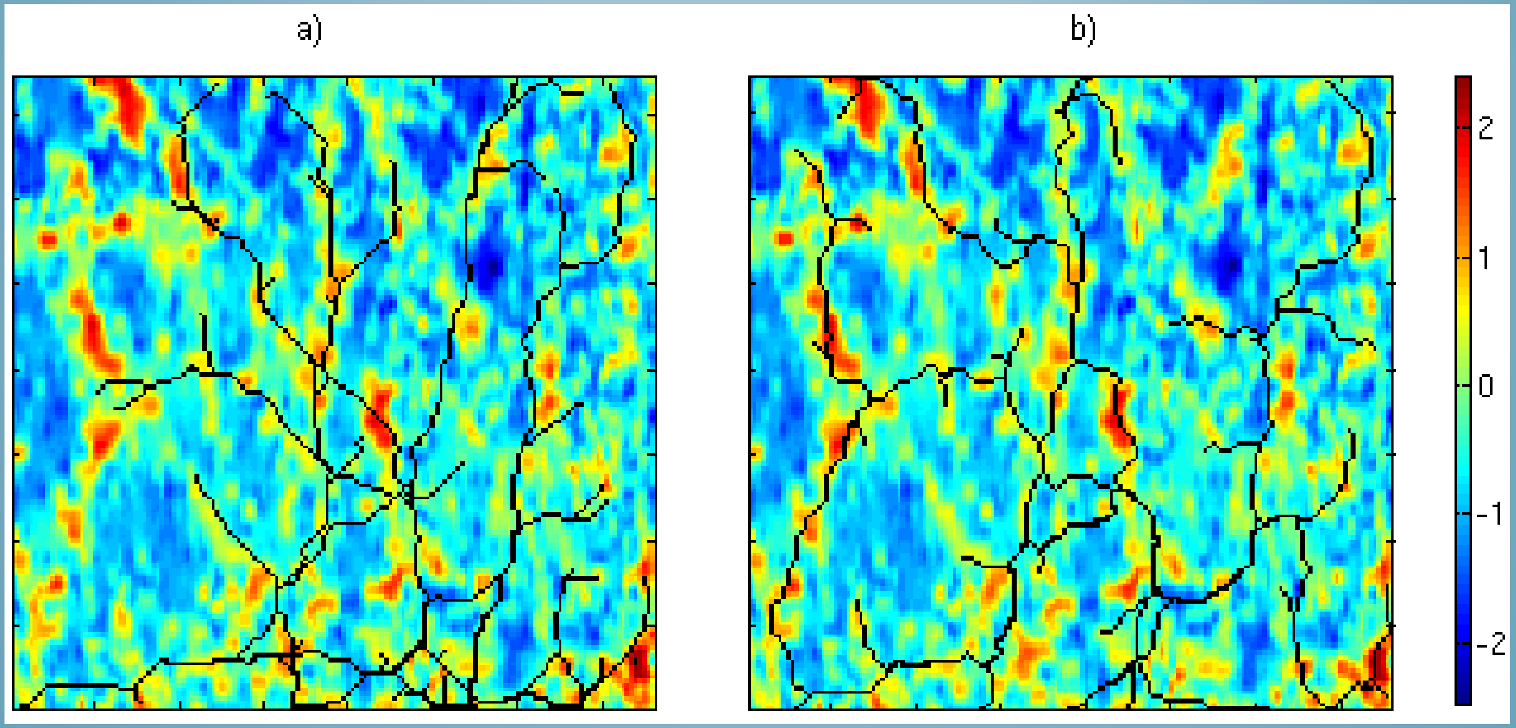
- Statistical analysis of distribution of Karst structures enables numerical stochastic simulation/generation of Karst network (Center for Geohydrology and Geothermics, University of Neuchatel).

- AEM plus adapted data processing can deliver important 3d-information about difficult accessible Karst systems in short time.

Hydrological modeling – Karst simulator

Stochastic Modelling Group (Philippe Renard), Center for Hydrogeology and Geothermics,
University of Neuchatel, Switzerland.

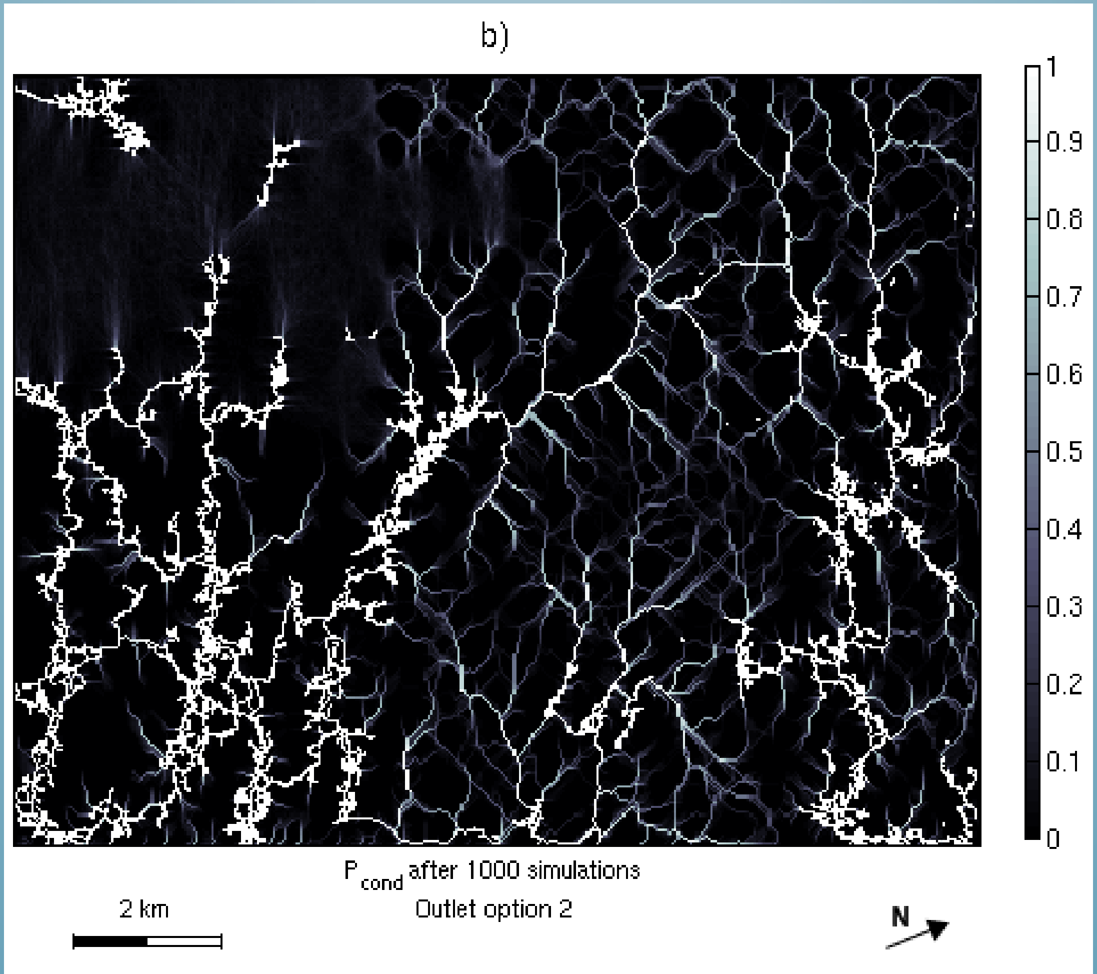
Realisations of conduit nets governed by AEM and cave survey data.



Weak weighting of AEM data

Strong weighting of AEM data

Hydrological modeling – conduit probability map



Hydrological modeling – simulation results

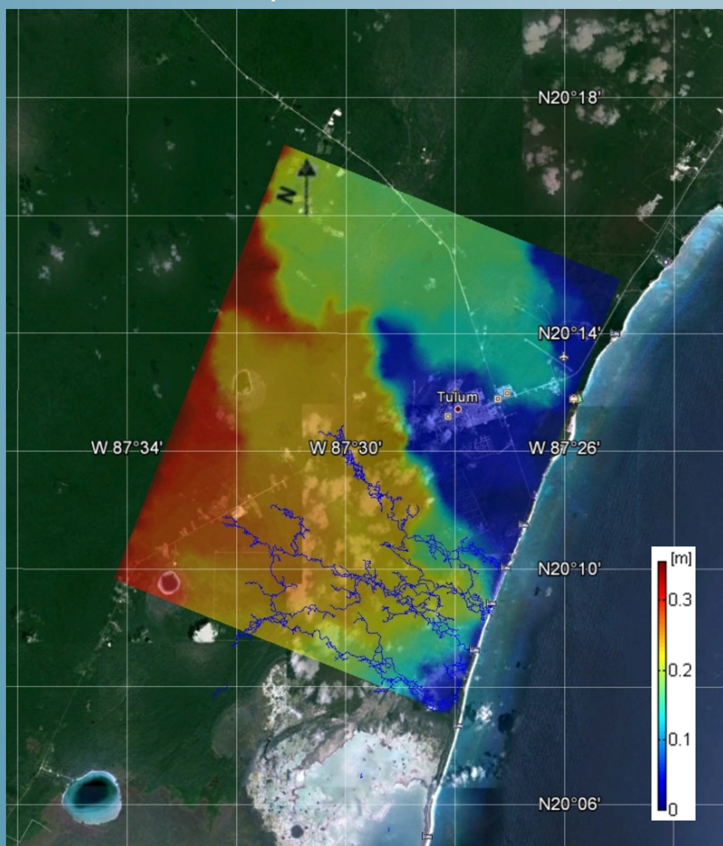
(P. Renard, C. Vuilleumeier, G. Kaeser, University of Neuchatel)

Simulated flow velocities through conduits: 0.63-0.93 m/s.

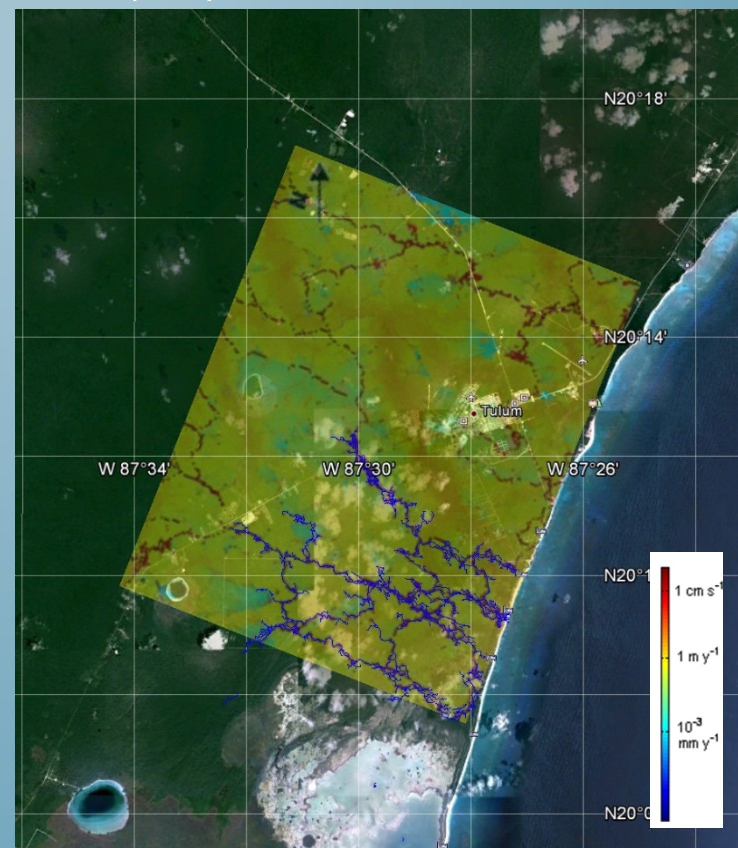
Major part of the flow passes through the conduits.

=> Flow traveltime from Tulum town to the sea very short.

Piezometric map hmax= 0.36 m



Velocity map vmax=0.75 m/s



Project Xibalba:
Acquisition of medium scale parameters for hydro-modelling
- 3D geometry laser scanning in underwater karst tunnels

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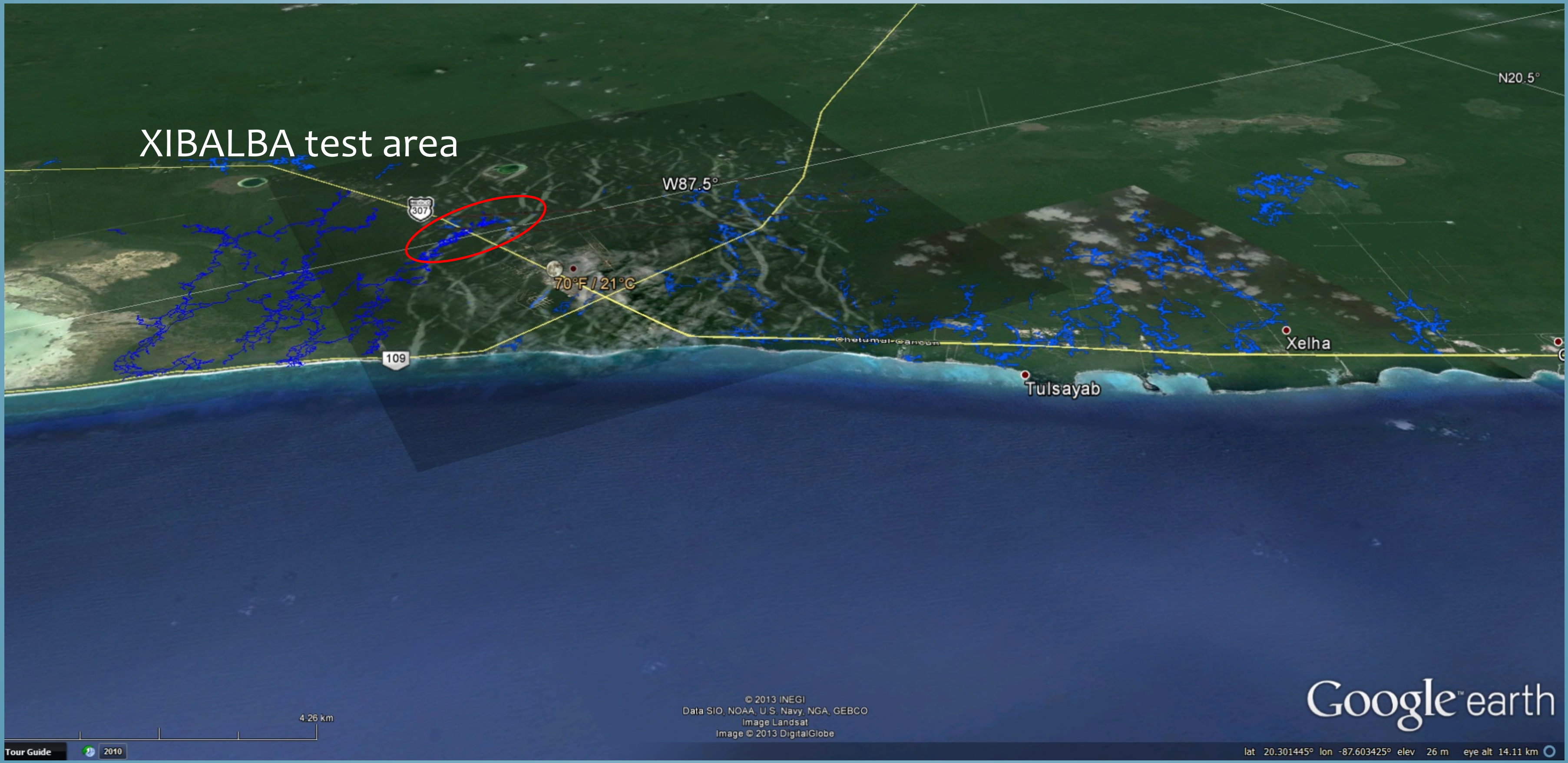
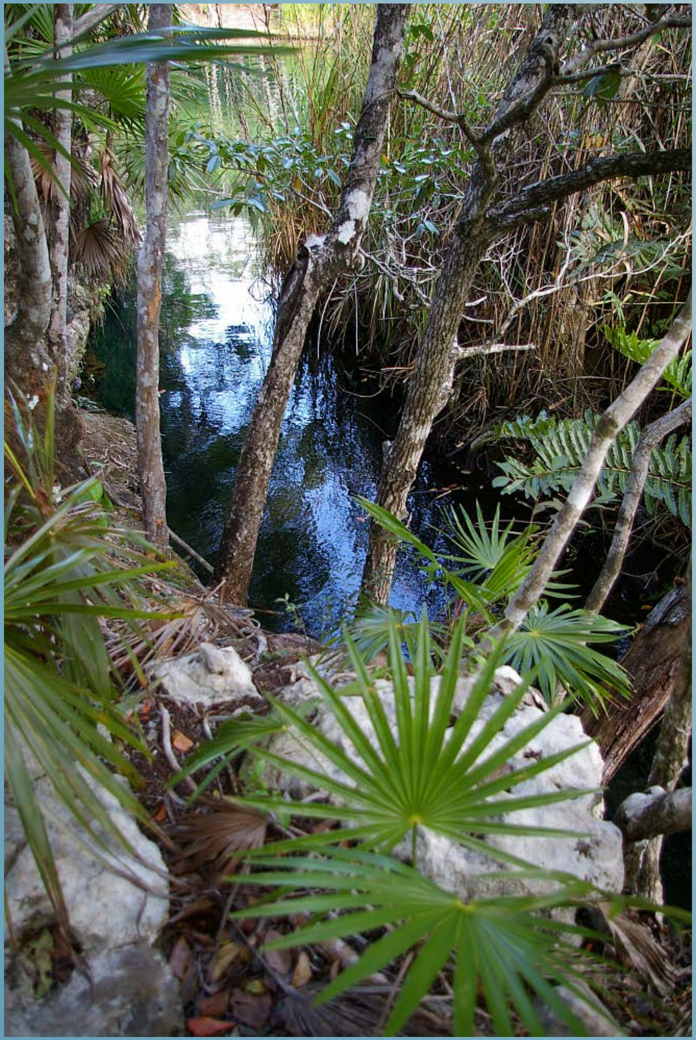
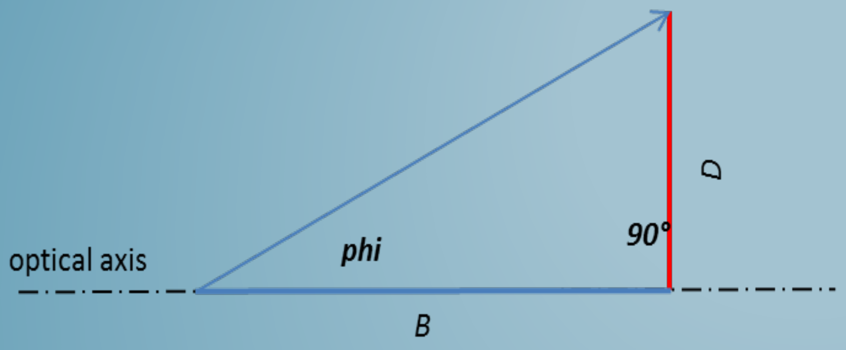
‚The whole thing‘ – system surveyed by exploration divers

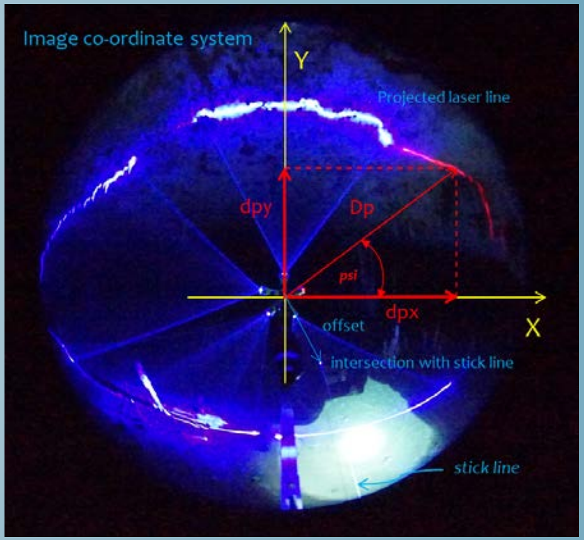


Cenotes



Basic Principle – Triangulation via Mapping





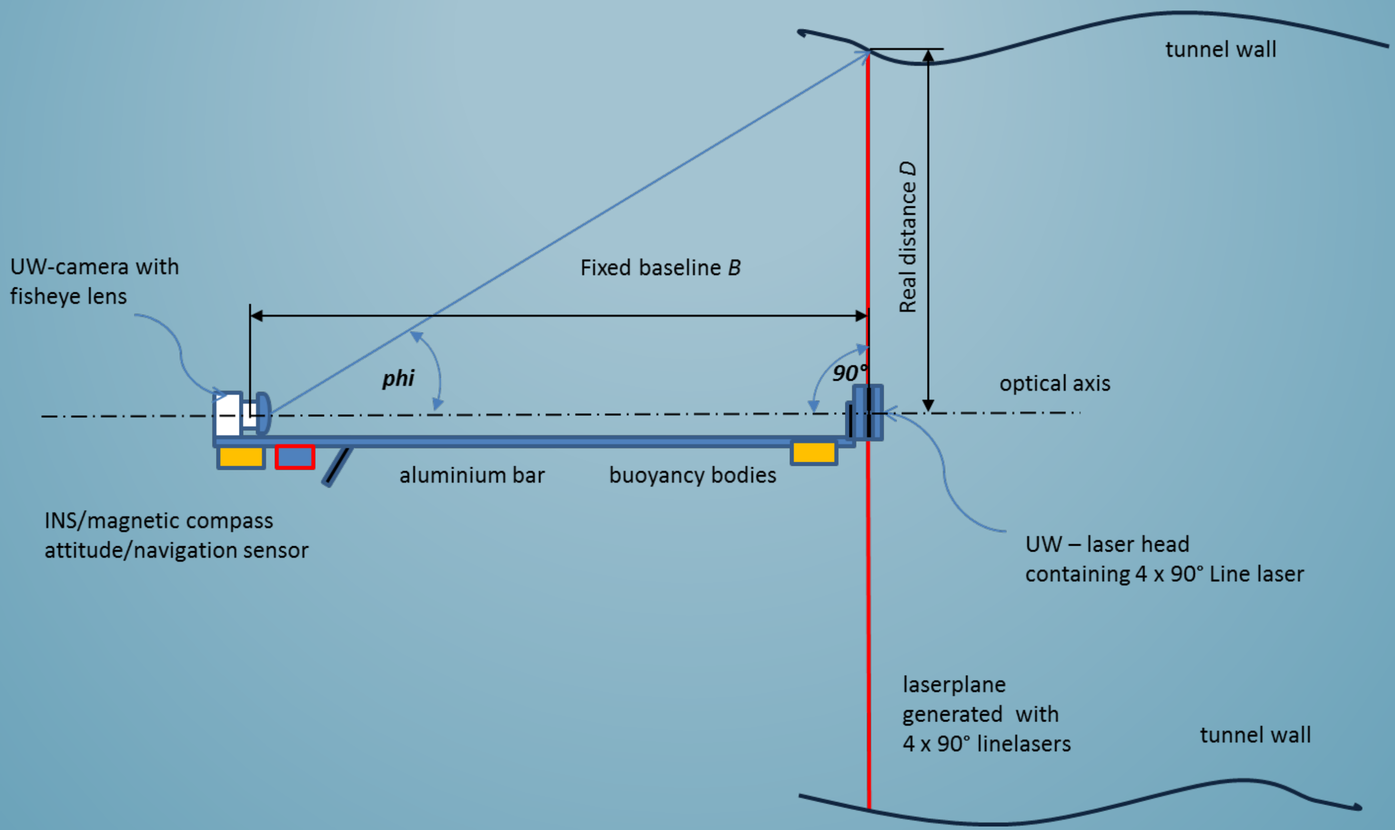
B: distance between a plane and the measurement location.
If plane normal to optical axis each distance in the plane can be derived from angle *phi* and distance *B*:

$$D = B \cdot \tan(phi)$$

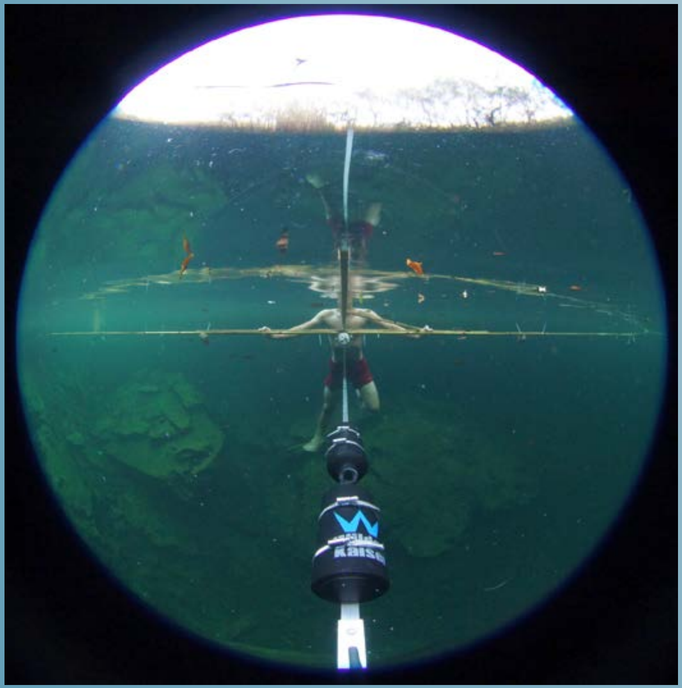
phi can be measured by means of an imaging system if relation between pixel distance in image *Dp* and *phi* can be expressed by a mapping function $D_p = f_m(phi)$. This relation depends on lens system.

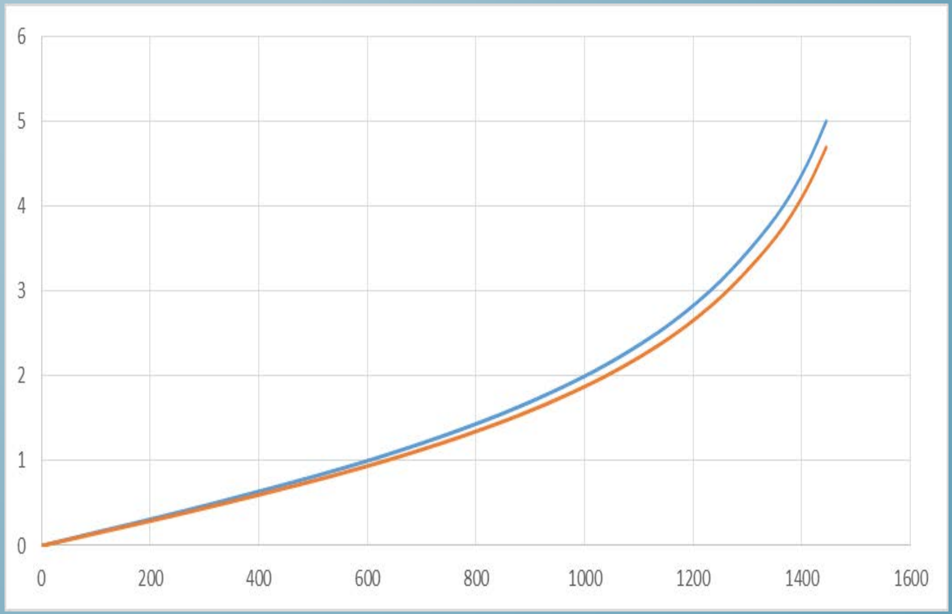
Thus $$D = B \cdot \tan\left(f_m^{-1}(D_p)\right)$$

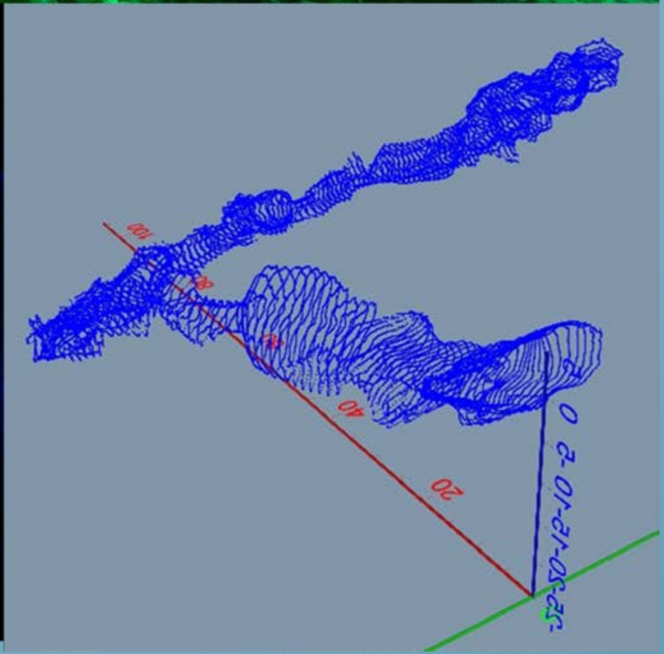
Principle of a mobile measurment set up for cross section capturing of under water caves



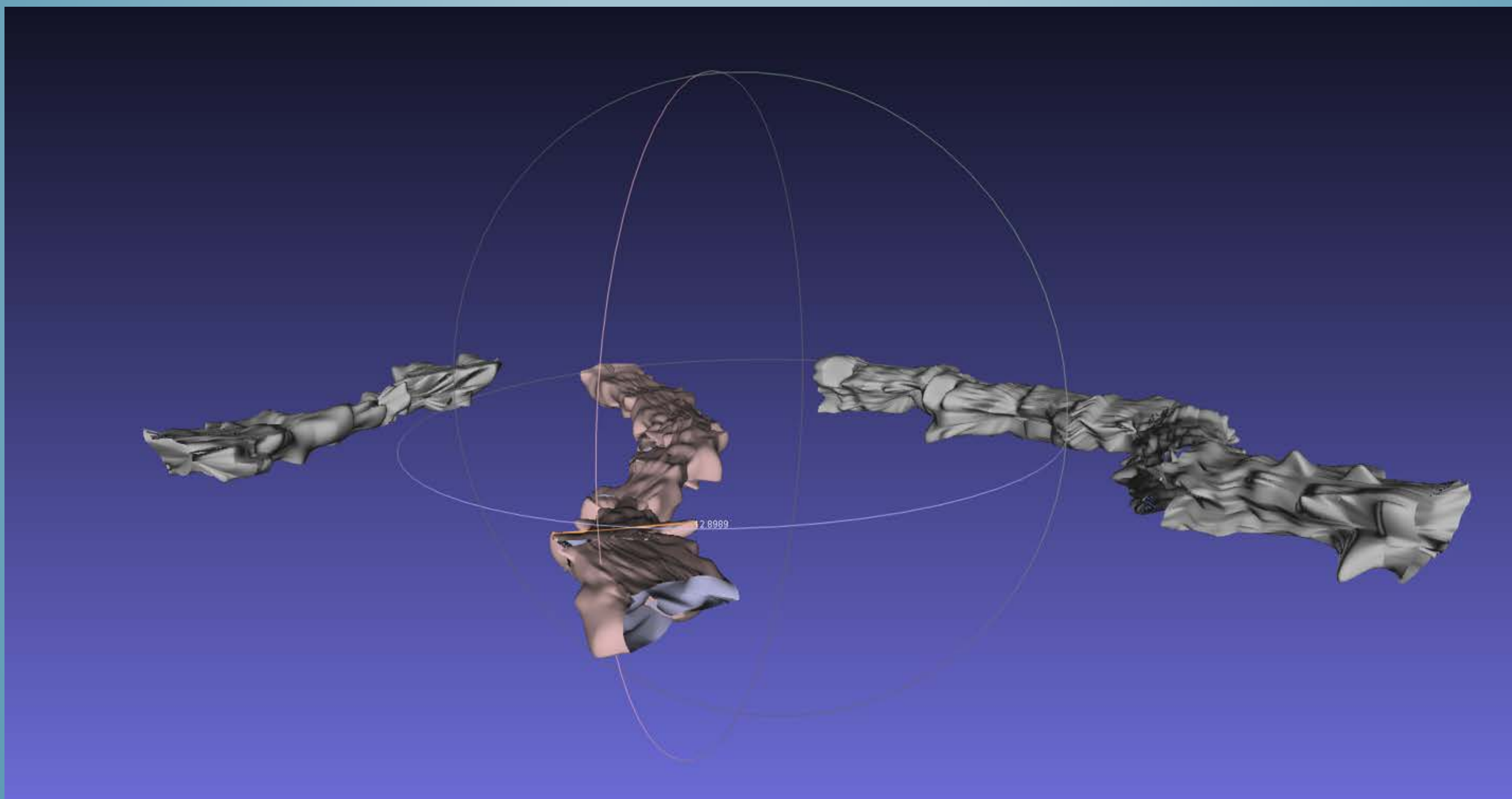
Laserscanner - Calibration for B=2m (2,03m)







Scans Cenote Cristal, Jailhouse, Tercier Cielo (2015)



Project Xibalba:
Experimental Laser Flux Imaging System

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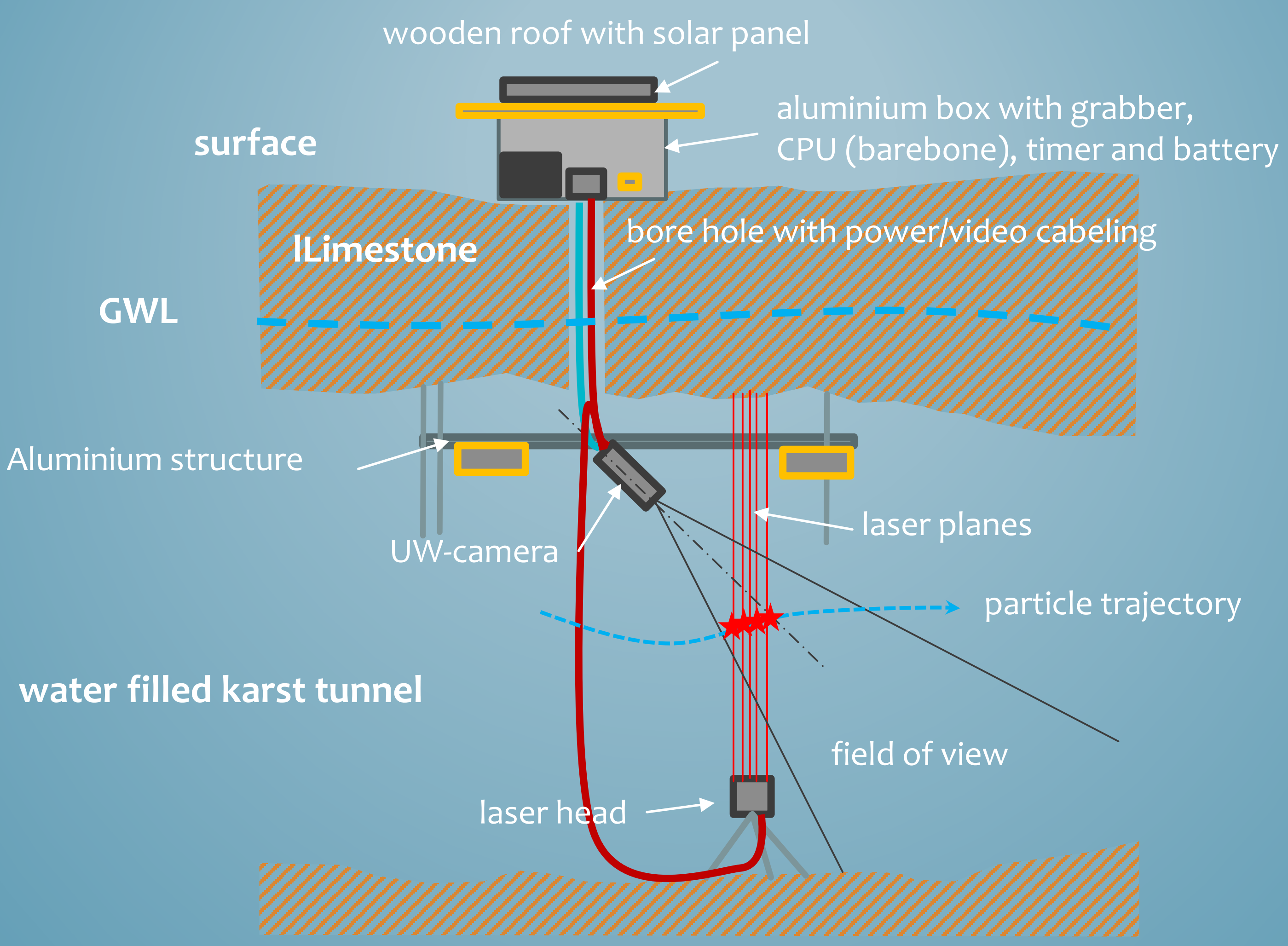
BASIC IDEA AND SET UP



RAW DATA

- Sample Screen shots ds=1.2 cm

t1=0.595

t2=1.786

t3=2.989

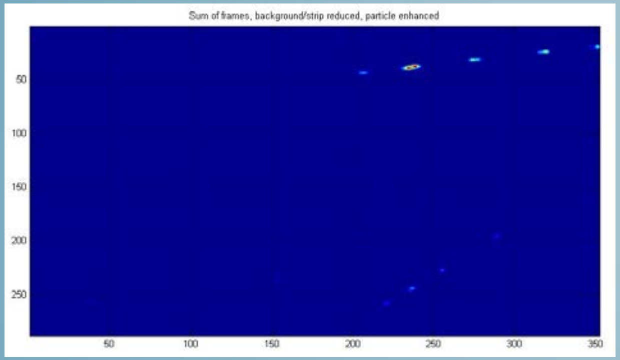
t4=4.481

t5=5.955

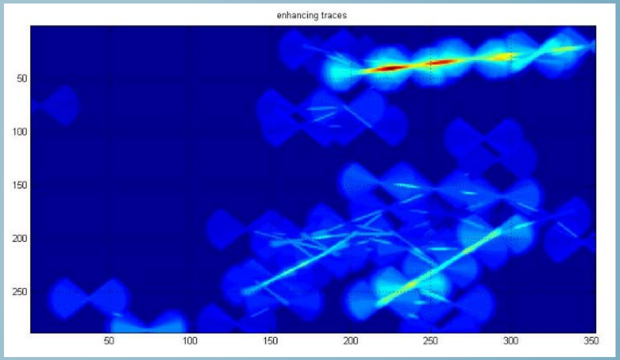
t	dt	v	
0.595			
1.786	1.191	1.01	
2.989	1.203	1.00	
4.481	1.492	0.80	
5.955	1.474	0.81	
normal	mean v	0.91	cm/s

Data Processing

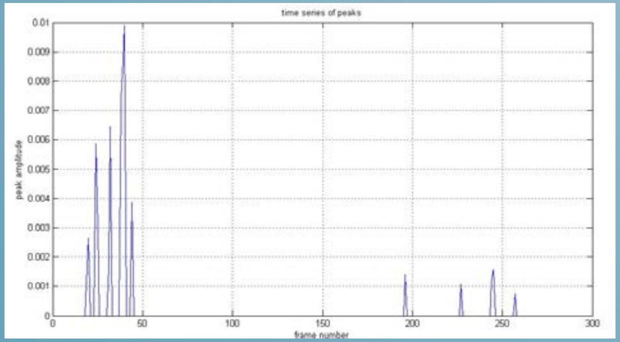
Particle enhancement



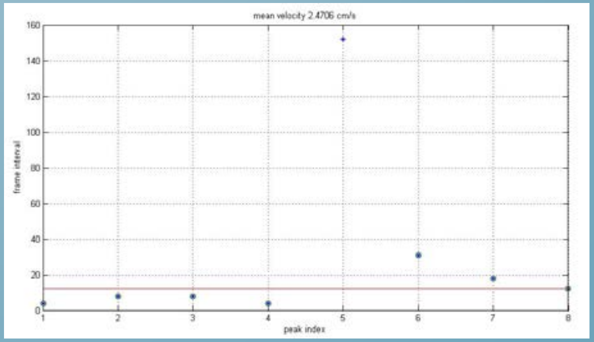
Searching traces



Finding peak series



Deriving velocities



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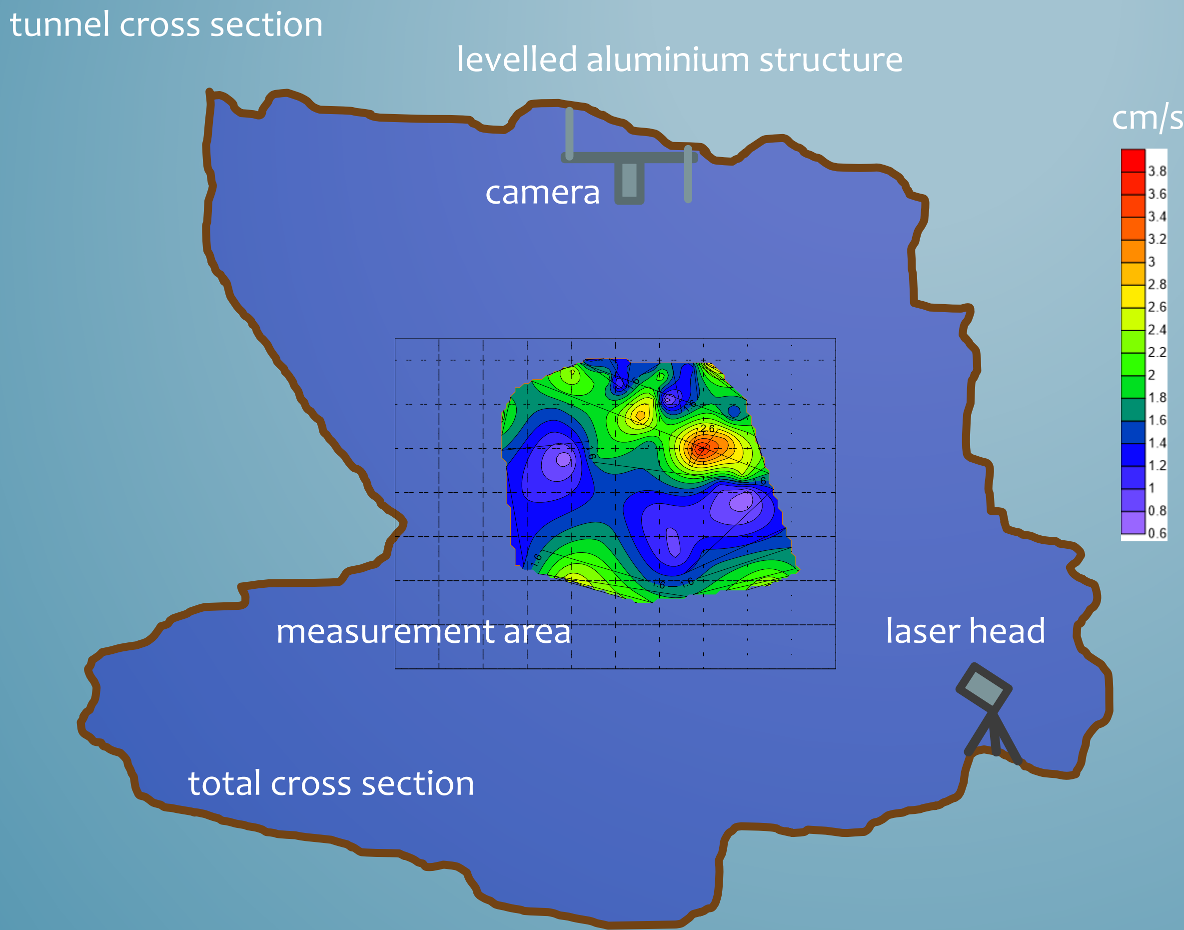
TRUE SCALE NORMAL VELOCITY FIELD AND FLUX ESTIMATION



Planar area:

Positive Planar Area: 1.176 m^2

Flux through area:

Total volumes by: cm³/s

Trapezoidal Rule:	20160.1
Simpson's Rule:	20133.8
Simpson's 3/8 Rule:	20159.1

Flux: 20.15 liters/s

(extraploated to whole cross section up to 200l/s)

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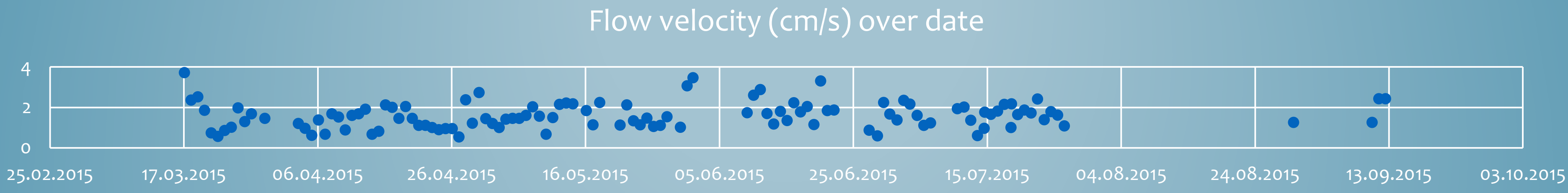
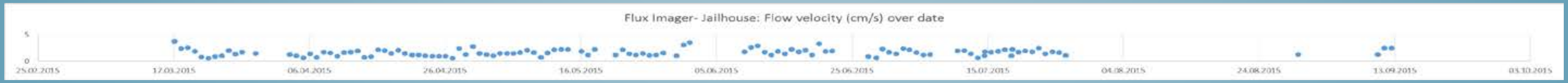
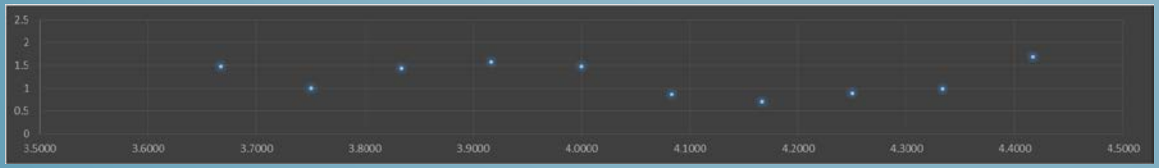
Flux Imager Jailhouse station

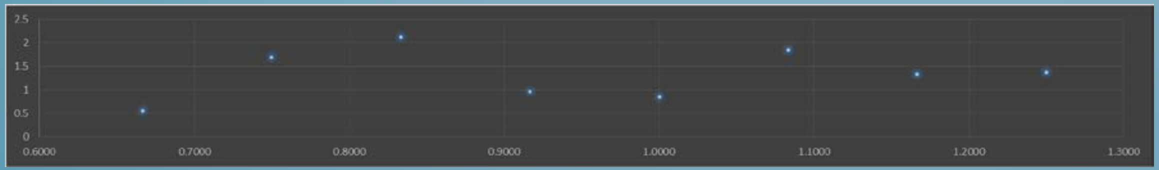
Long term series



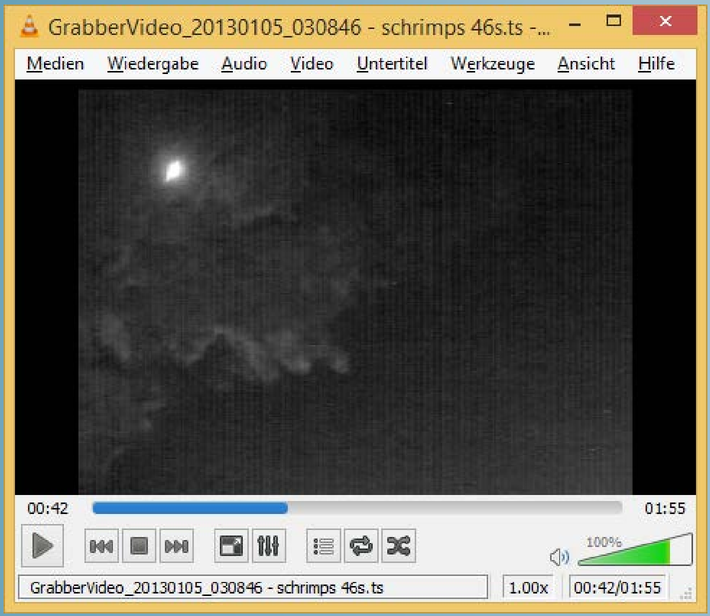


Short term variations – time interval 2 hours





INTERFERING PHENOMENA - STYGIOBIONTS



Right: Niphargus ictus (http://en.wikipedia.org/wiki/Niphargus)

Left: Proasellus cavaticus (http://www.karstforschung.at/H%F6hlenfauna.htm).

CONCLUSION

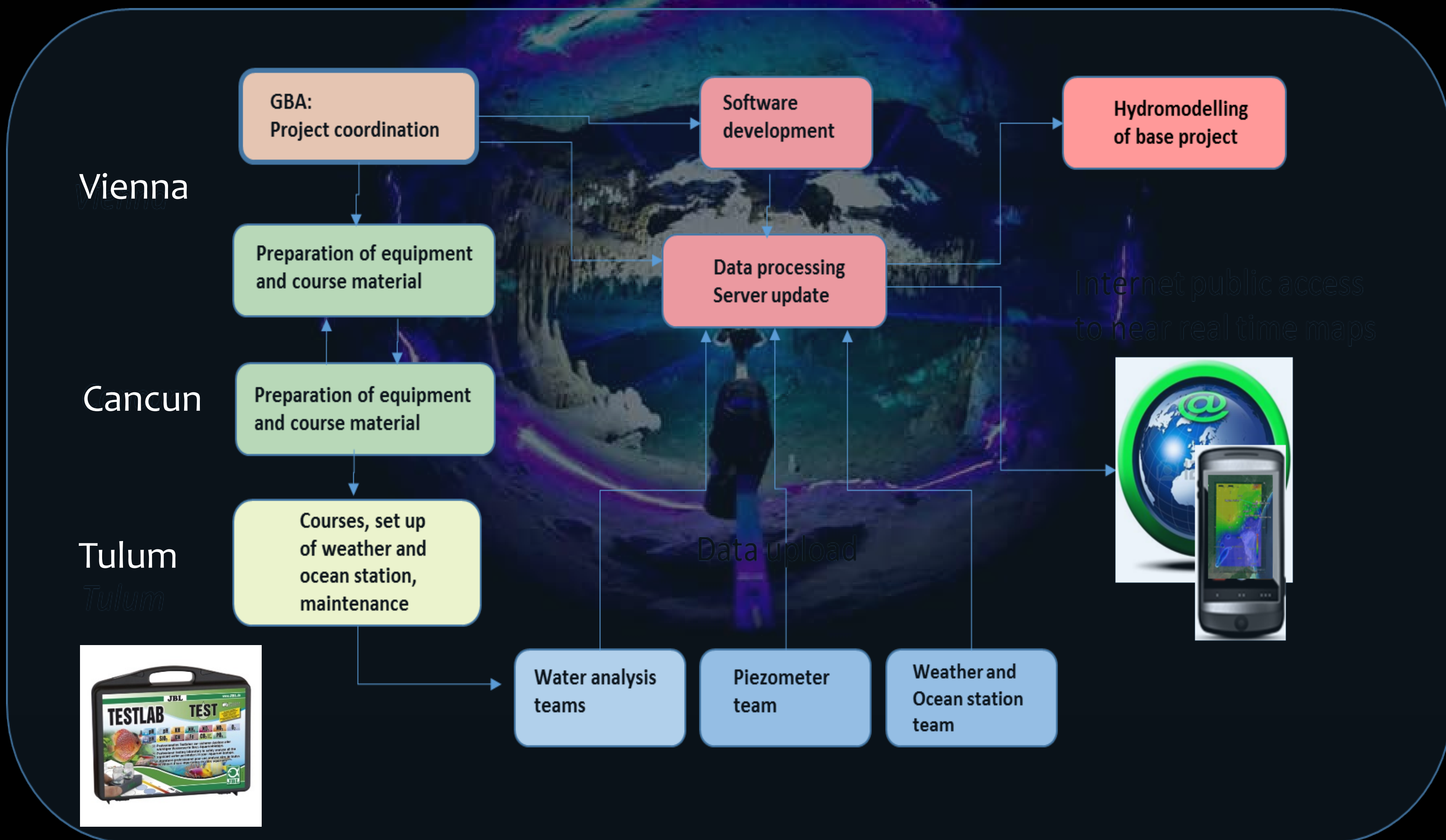
- Slow turbulences imagable - complex temporal/spatial velocity field
- Improved flux estimation
- Variations with periods T ≈ 0.5 days, amplitude 0.25-0.5 cm/s
- Superior resolution of low velocities
- Clear water/ darkness required

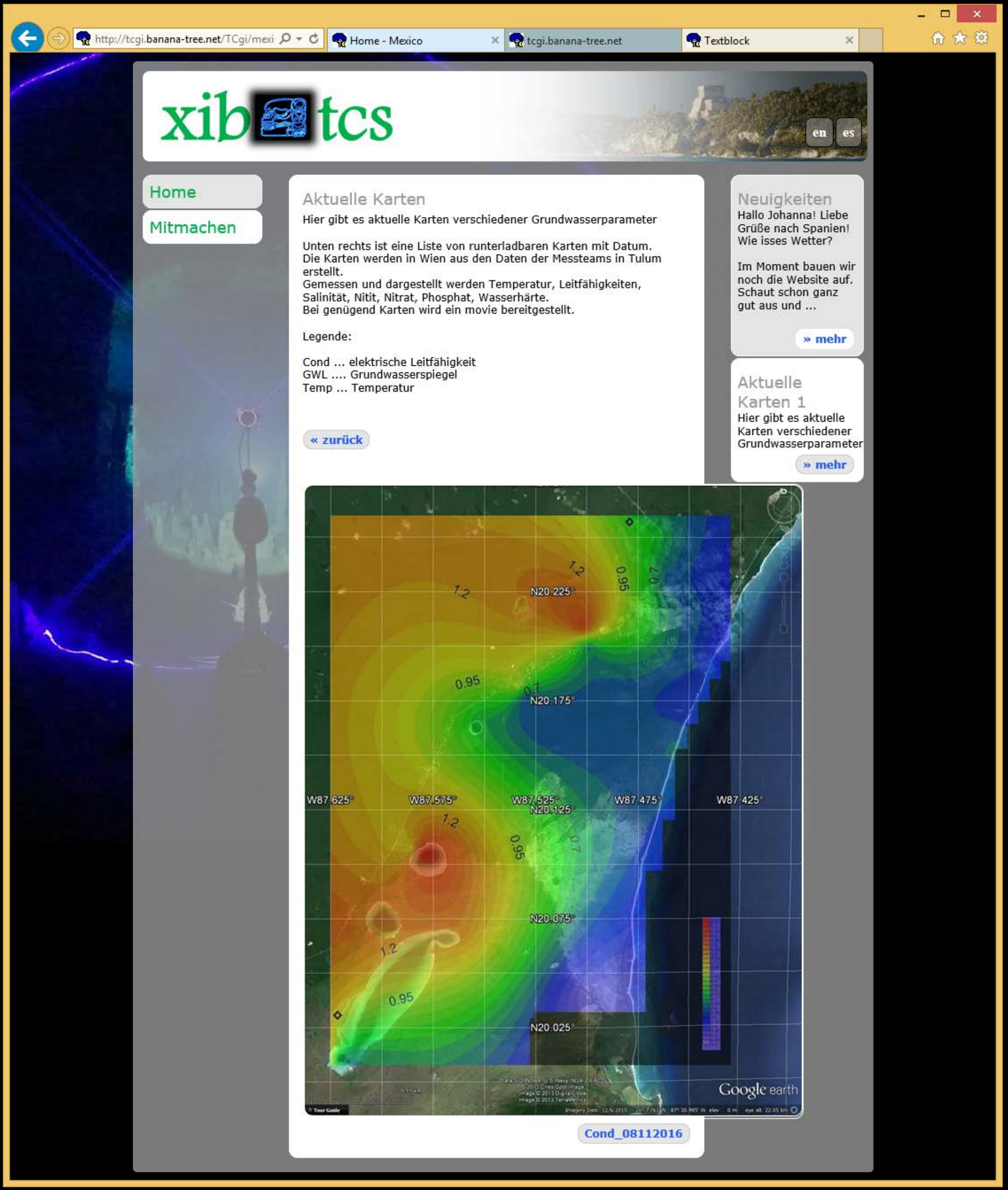
Next Steps:

- Improving full automatic image processing
- Data reduction on site
- Extension to wider measurement area
- Artificial particle generation (electrolysis)
- Full autonomous system (under water battery)

Project Xib_TCS:

Citizen supported groundwater monitoring in Tulum





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El Paraiso


Gracias!