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Application of InSAR for Monitoring Deformations at the Kiirunavaara Mine

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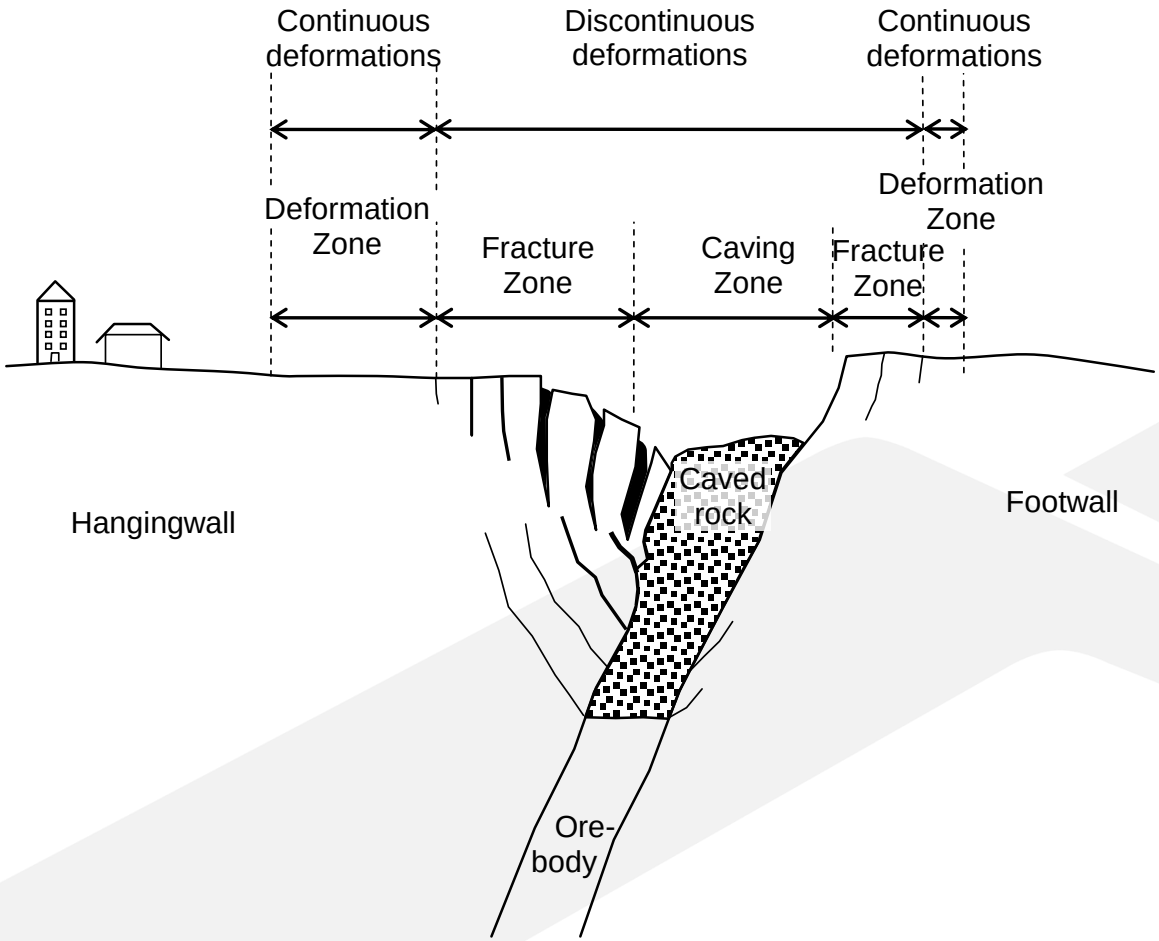
SUBLEVEL CAVING = GROUND DEFORMATIONS



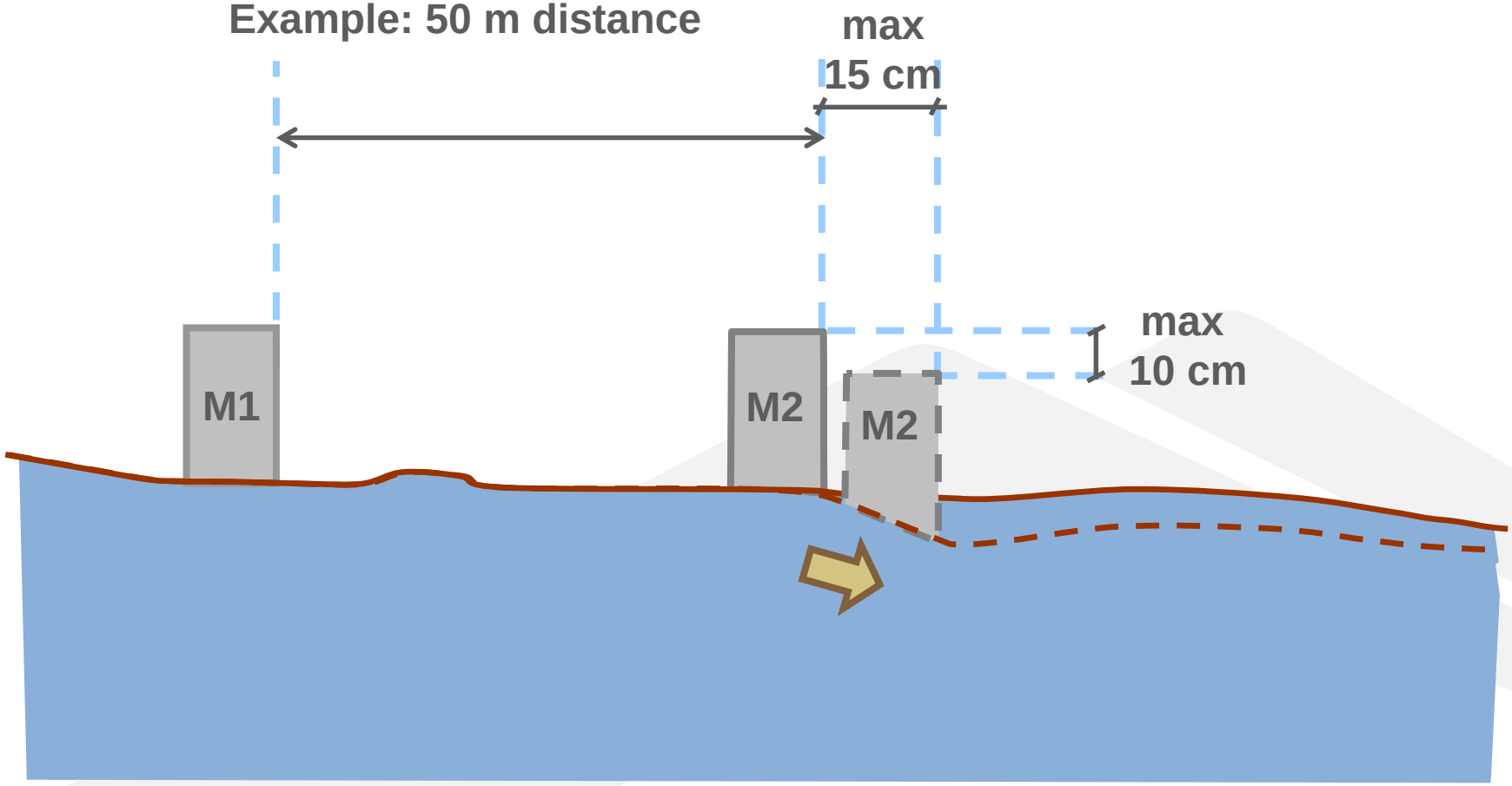
KIRUNA


City of Kiruna
E10 Highway
Hangingwall side
City Hall
Old Railroad
LKAB Kiirunavaara Mine
North
Footwall side

ENVIRONMENTAL DEFORMATION CRITERION

Strain limit – 3 ‰ horizontally, 2 ‰ vertically

Example: 50 m distance

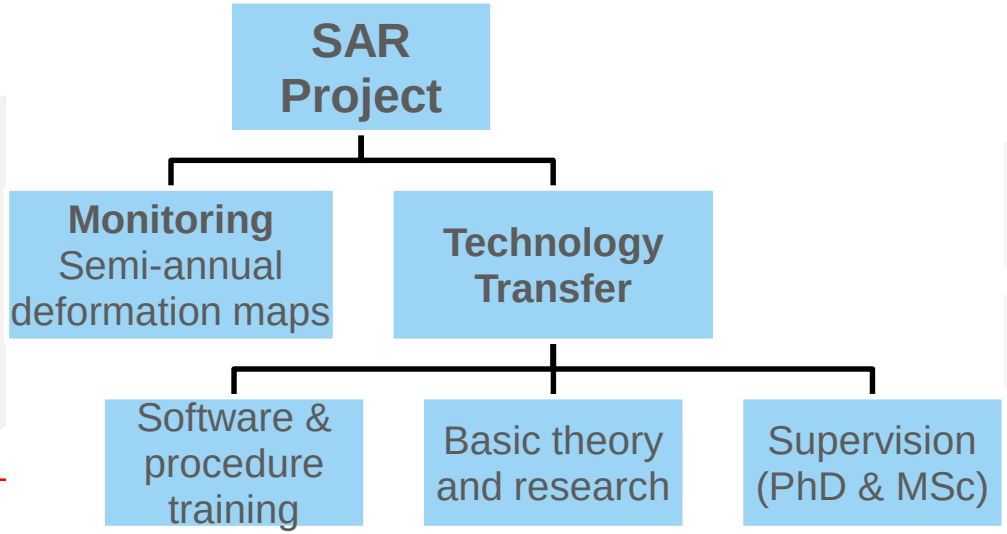


GPS MEASUREMENT NETWORK

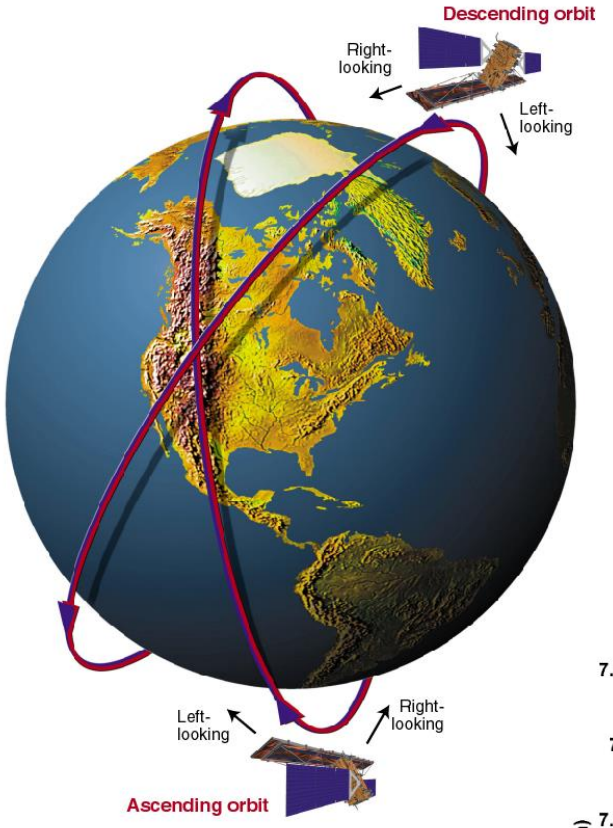
North

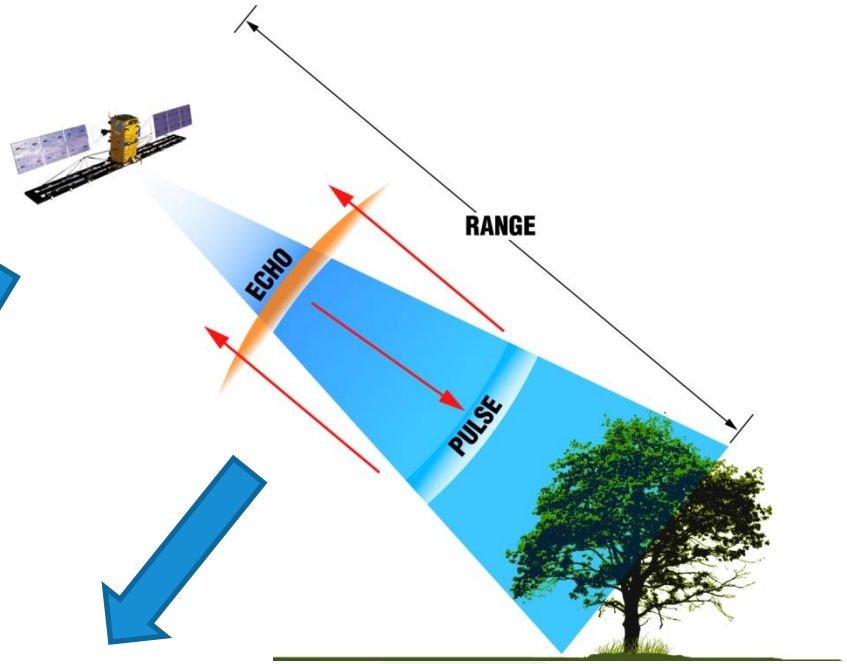
PROJECT DESCRIPTION

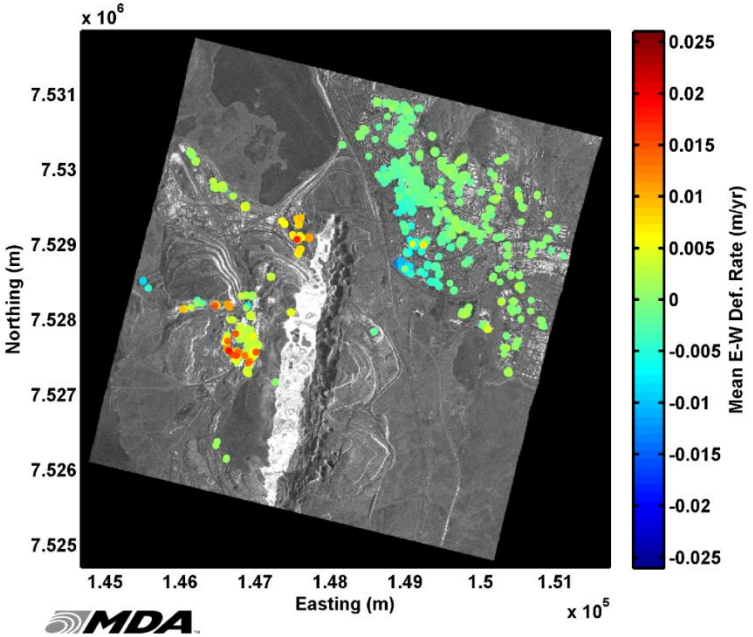
- Assess the use InSAR technology for LKAB's purposes — as a replacement and/or complement to current GPS measurements
- Further develop the InSAR technology for winter conditions at high latitudes, aiming at improving precision
- Conduct a technology transfer to LKAB with the goal of LKAB being able to produce results (deformation maps) in-house from satellite data



INSAR MONITORING TECHNOLOGY







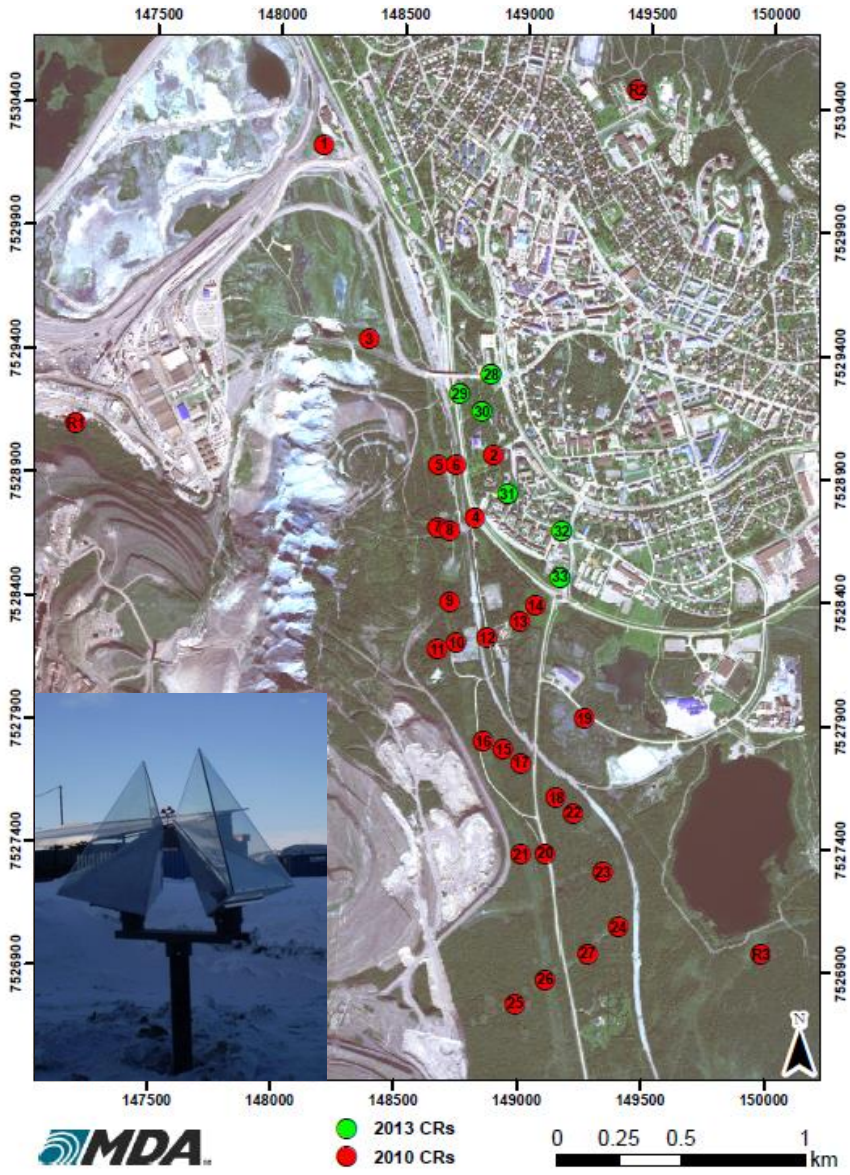
INSAR TECHNOLOGY

- Wide area monitoring (DInSAR)
- Point analysis
  - Corner Reflectors (CR)
  - Coherent Target Monitoring (CTM)

- All monitoring techniques applied and tested in Kiruna
  - Historic analysis conducted initially to confirm applicability
  - Development of monitoring program including DInSAR, CTM, PSInSAR and CR (for areas with little or no backscatterers)
  - RADARSAT-2 satellite data used for entire project; 24 day return period, 3 beams used (later 2 beams)

MONITORING IN KIRUNA

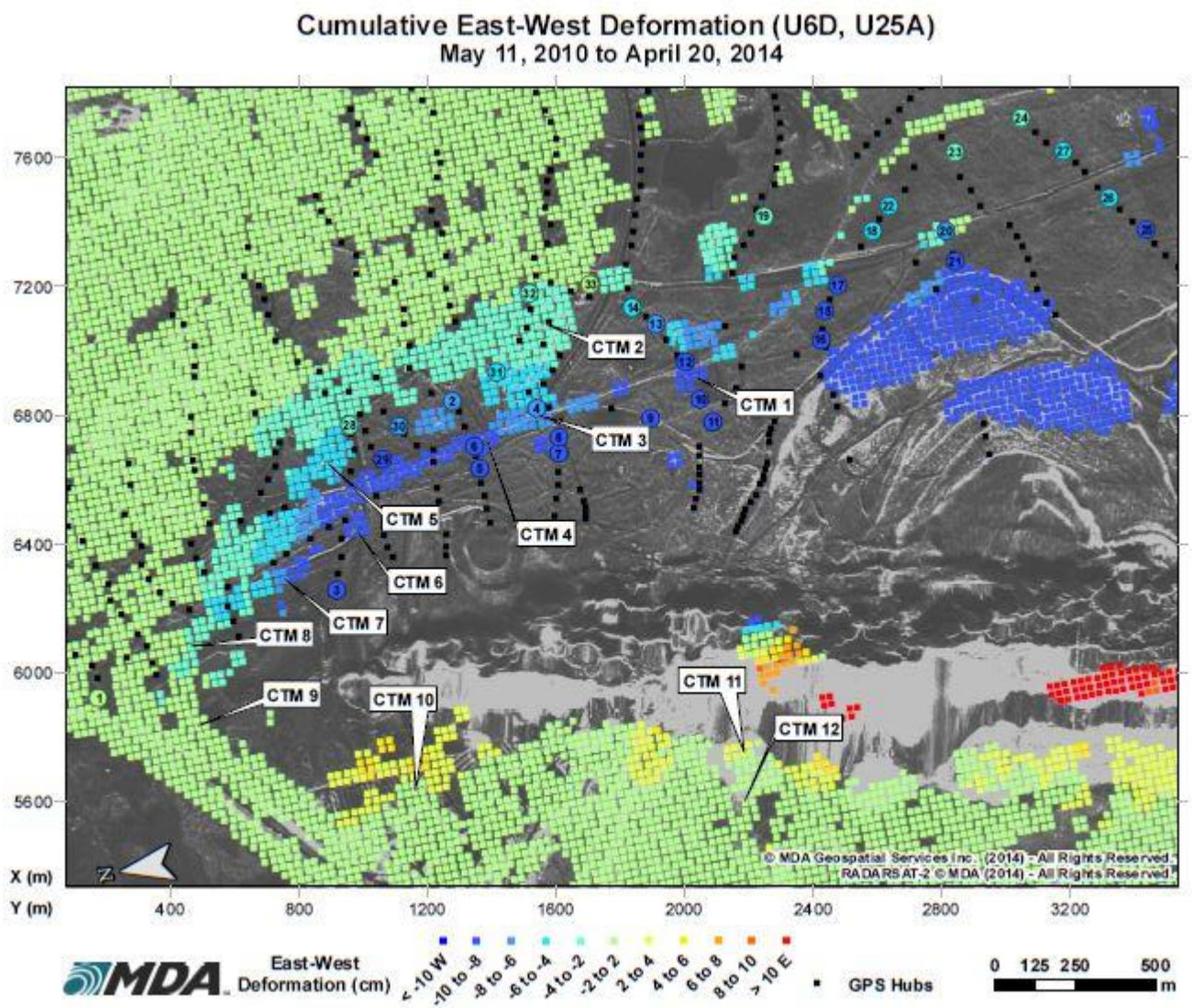
- CR network installed; 60 + 6 dual corner reflectors at 33 locations
- CTM for natural / artificial reflectors (mostly existing infrastructure; > 20 000 points)
- DInSAR deformation maps
- Result delivery every 6 month:
  - Satellite imagery
  - Deformation maps
  - Time series profiles CR & CTM



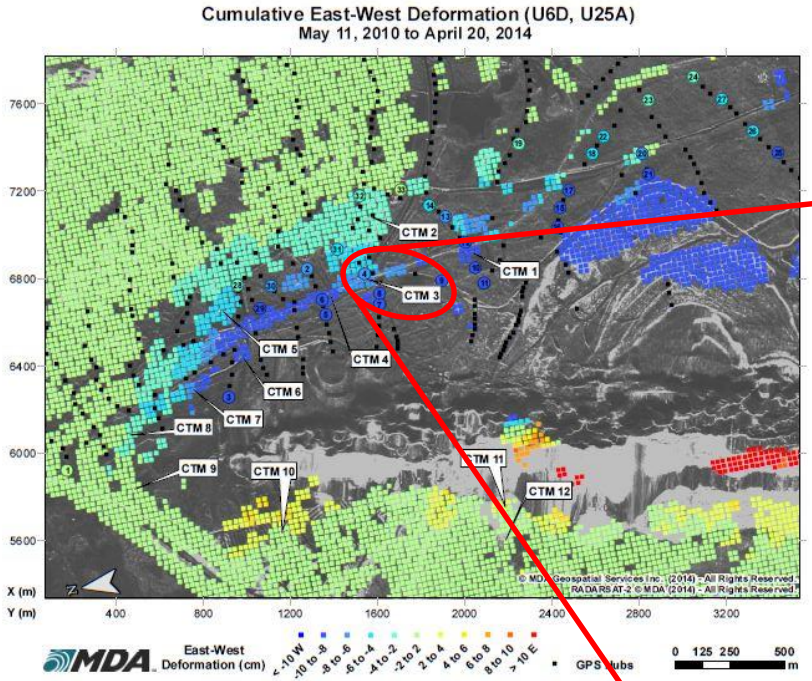
SELECTED PROJECT RESULTS

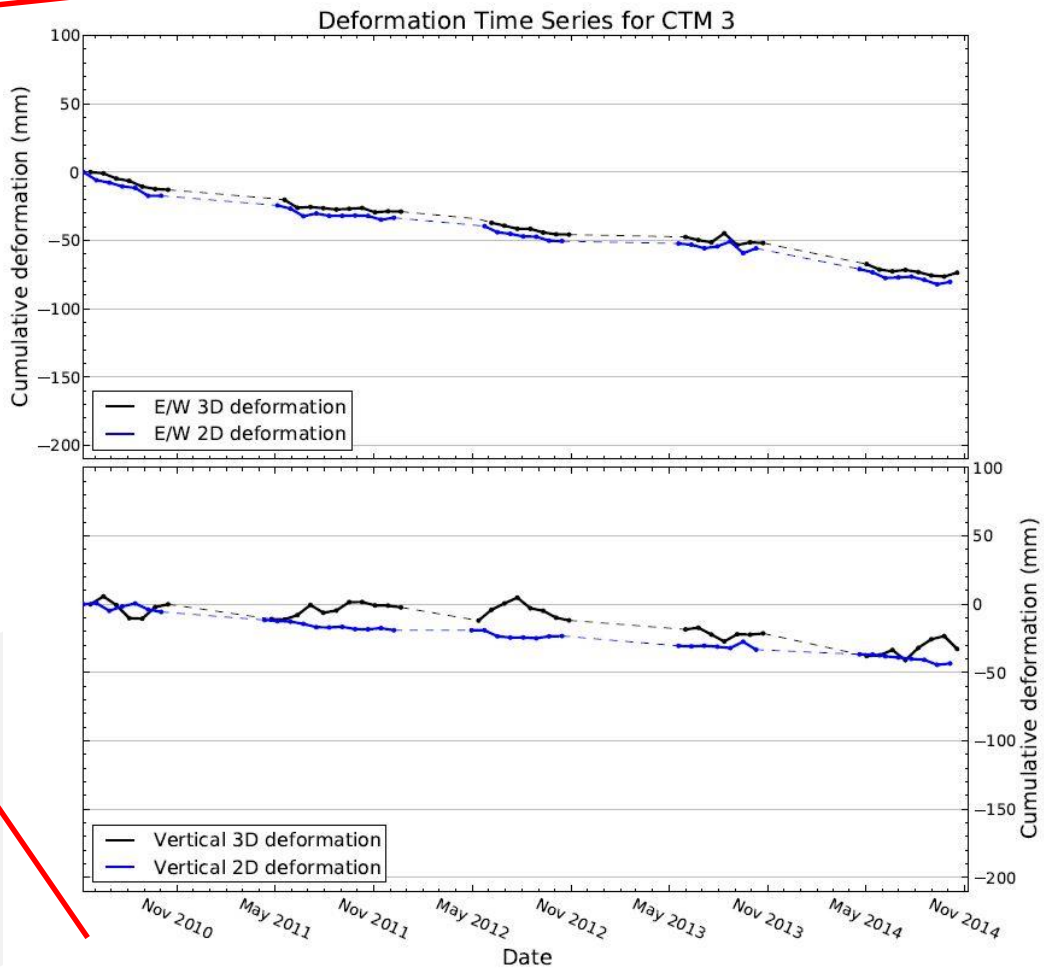
- **Accuracy Assessment**
  - Poor accuracy for N-S deformations due to polar orbit of satellites
  - Line-of-sight as well as E-W and vertical decompositions more reliable
  - Preferred set of 2D decompositions reduced uncertainty further:
    - CR: 2 mm in E-W and vertical direction
    - CTM: 4 mm in E-W direction; 3 mm in vertical direction
- **Monitoring Data**
  - DInSAR deformation maps for assessing overall trends
  - CR time series plots
  - CTM "maps" & selected points for time series plots

CTM "MAP" & SELECTED CTM POINTS



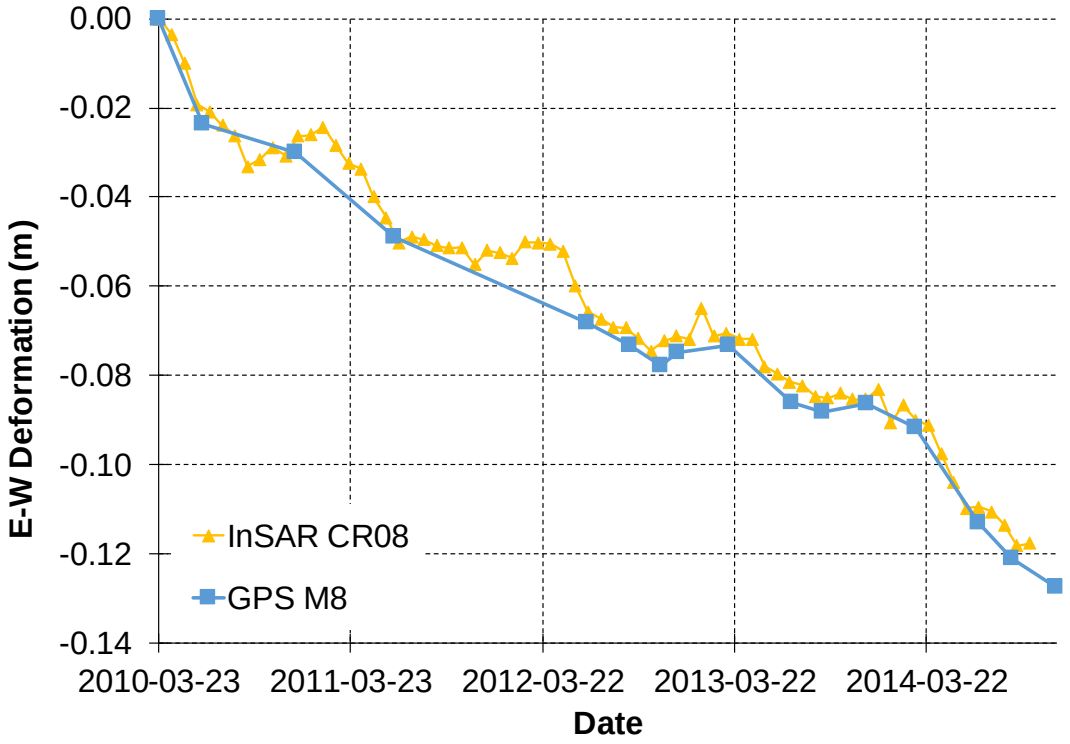
CTM "MAP" & SELECTED CTM POINTS





SELECTED PROJECT RESULTS

- **Comparison with GPS Data**
  - Comparison at neighboring GPS and CR points, plotted for the same time period
  - Very good agreement in both trend and magnitude of ground deformations
  - Increased trust-worthiness in InSAR results!



SELECTED PROJECT RESULTS

- **Seasonal Coherence Variation**
  - Snow layer reduced coherence; fewer suitable winter images
  - Good summer-summer coherence; use summer image as master image to achieve high coherence
- **Technology Transfer**
  - Build-up of knowledge and know-how within LKAB
  - High-level & targeted training provided by MDA to LKAB, including software and hardware tools
- **Strain Calculations**
  - Important to determine location of envirionmental criterion limit
  - InSAR CR measurements used to assess location
  - Reasonable agreement with GPS; additional fine-tuning required

STRAIN CALCULATION COMPARISON

Measurement points	Horizontal strain [‰]		Vertical strain [‰]	
	GPS	InSAR (CR)	GPS	InSAR (CR)
M7-M8	0.79	0.4-0.5	0.49	0.3-0.4
B14-C20	0.67	> 0.7	0.47	0.5-0.6
D50-D53	0.53	0.4-0.5	0.08	0.1-0.2
L8-L10	0.40	0.3-0.4	0.46	0.4-0.5
L10-L14	0.47	0.4-0.5	0.23	0.2-0.3
S13-S15	0.03	0.2-0.3	0.11	0.3-0.4
B14-F51	0.39	0.5-0.6	0.33	0.5-0.6
M8-M12	0.40	0.4-0.5	0.26	0.3-0.4
H13-H12	0.71	> 0.7	1.35	0.6-0.7

CONCLUSIONS

- **InSAR** allows measurements over large areas with fewer measurement hubs (CRs) compared to GPS measurements
- **DInSAR** deformation maps worked well for identifying trends and patterns in ground deformations, but dependent on having high coherence between image pairs
- **CR** & **CTM** provided high-precision data for specific points, and (nearly) year-round coverage
- **CTM** particularly appealing (no installations needed) but susceptible to ambiguous phase unwrapping; large number of CTMs help reducing this uncertainty + supplement with CRs in areas with poor coverage
- **E-W** and **vertical** deformations components satisfactorily analyzed; not possible to achieve acceptable accuracy for N-S deformations

RECOMMENDATIONS

- Continue InSAR measurements in Kiruna as a complement to current GPS measurement – focusing on point analysis (CR & CTM)
- Additional CR should be installed in areas with poor CTM coverage and poor back-scatter
- Additional work on comparing CR & CTM InSAR data with GPS measurement, to further "ground truth" the InSAR data
- More work on coherence effects and winter images warranted; robust methodology for data analysis required
- Evaluate alternative measurement techniques for monitoring of mining-induced ground deformations, e.g., automated GPS, automated total station, UAV photogrammetry, UAV LiDAR, etc

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Thank you for your attention

PERFORMANCE IN IRONMAKING