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Rapid Geocoding of Satellite SAR Images with Refined RPC Model

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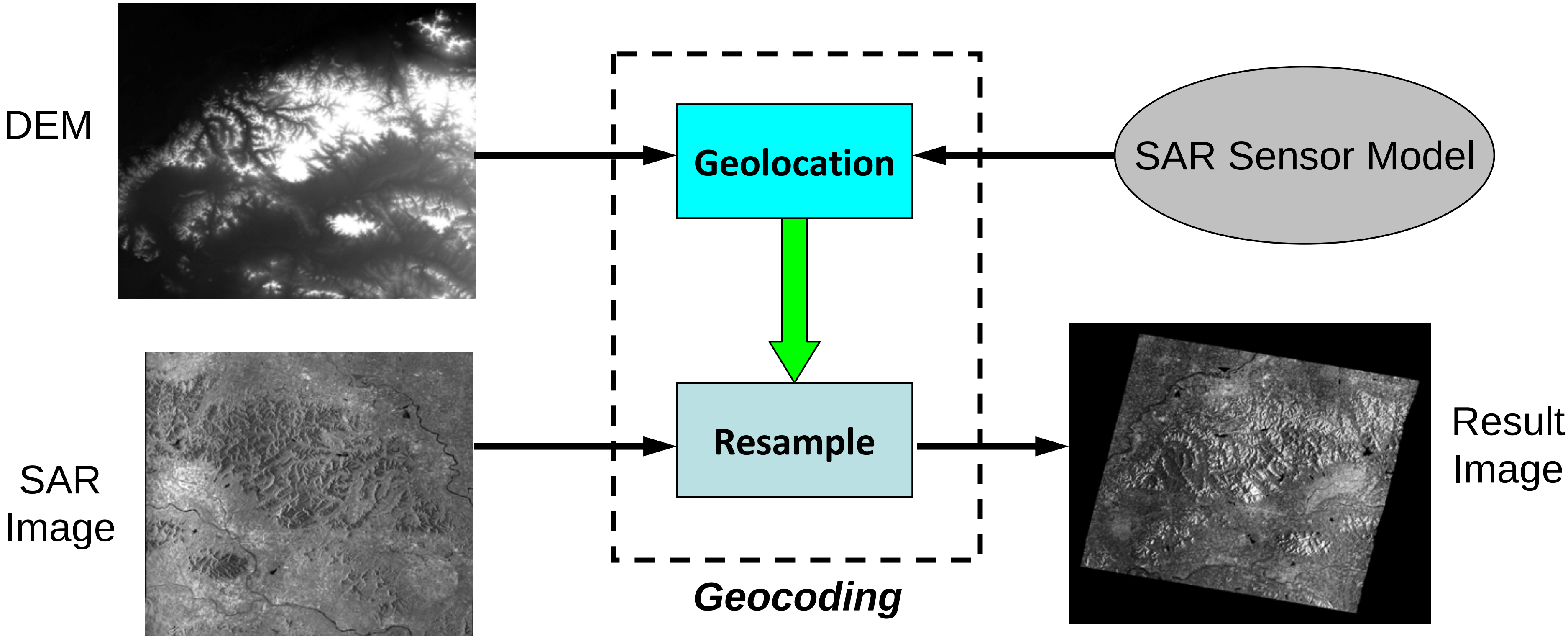
1. Introduction

- Geocoding of satellite SAR data is essential for:
  - removal of inherent geometric distortions (foreshortening, layover, shadow, etc.)
  - output of SAR data processing and analyses
  - joint analyses of SAR data with other geospatial datasets (optical image, raster, vector, etc.)

- Basic principle of SAR geocoding



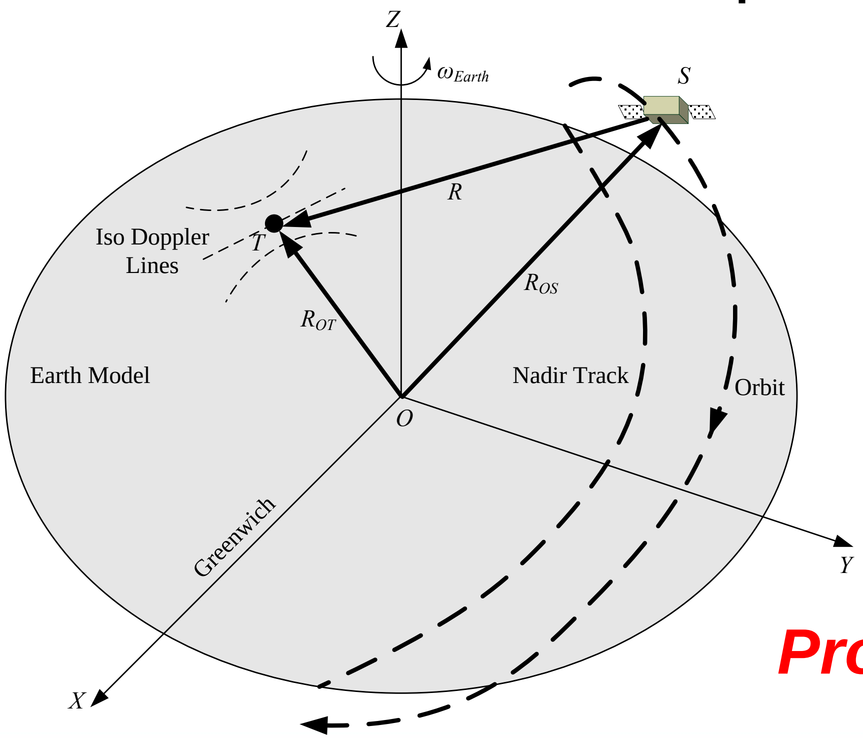
- SAR sensor models
  - Primary function: conversion between image pixel location (r, c) and geographic coordinate (lat, lon, hgt)
  - Category:
    - Rigorous physical models

      Range-Doppler (RD), Collinearity Equation
    - Generic/replacement mathematic models

      Polynomial, **Rational Polynomial Camera (RPC)**

- RD model *industry standard sensor model for SAR systems*

consists of three equations:



$$\begin{cases} R = \left| R_{OT} - R_{OS} \right| \\ f_D = \dfrac{2}{\lambda R}(V_S - V_T) \bullet (R_{OS} - R_{OT}) \\ \dfrac{X^2 + Y^2}{(R_e + h)^2} + \dfrac{Z^2}{R_p^2} = 1 \end{cases}$$

Problem: Solution by iterations!

- RPC model

$$\begin{cases} r = \dfrac{N_r(P,L,H)}{D_r(P,L,H)} \\ c = \dfrac{N_c(P,L,H)}{D_c(P,L,H)} \end{cases}$$

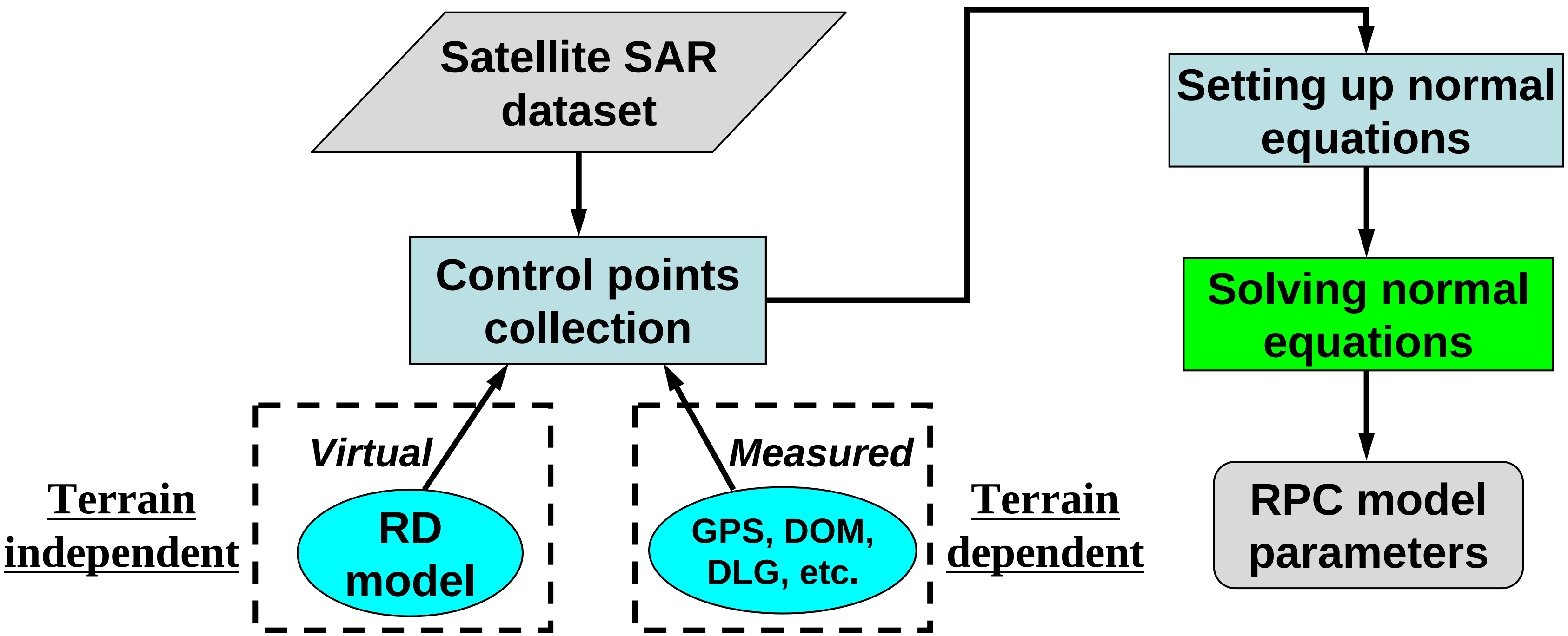
$$p = \sum_{i=0}^{m1}\sum_{j=0}^{m2}\sum_{k=0}^{m3} a_t P^i L^j H^k = a_0 + a_1 L + a_2 P + a_3 H$$
$$+ a_4 PL + a_5 LH + a_6 PH + a_7 L^2 + a_8 P^2 + a_9 H^2$$
$$+ a_{10} PLH + a_{11} L^3 + a_{12} P^2 L + a_{13} LH^2 + a_{14} PL^2$$
$$+ a_{15} P^3 + a_{16} PH^2 + a_{17} L^2 H + a_{18} P^2 H + a_{19} H^3$$

Advantages:

- unified formulation, easy programming
- high computation efficiency

2. RPC Modeling for Satellite SAR

- Basic workflow of RPC modeling



Methods	Computation Time (unit: seconds)	RSME (MAE) at CNPs (unit: 10^{-3} pixels)			RSME (MAE) at CKPs (unit: 10^{-3} pixels)		
		Line	Pixel	Planimetric	Line	Pixel	Planimetric
Ridge trace	5.5010	0.7835 (2.1634)	0.0733 (0.2671)	0.7870 (2.1635)	0.9830 (2.5888)	0.0855 (0.3453)	0.9867 (2.5891)
GCV	10.0019	0.1443 (0.6200)	0.0783 (0.4565)	0.1642 (0.6212)	0.2495 (1.6895)	0.1625 (1.1054)	0.2978 (2.0152)
L-curve	2.3663	0.2518 (1.2540)	0.0685 (0.2777)	0.2610 (1.2611)	0.4326 (2.2926)	0.0788 (0.3545)	0.4397 (2.3006)
ICCV	216.0392	0.1011 (0.3774)	0.0331 (0.2602)	0.1064 (0.4211)	0.1773 (0.9825)	0.0866 (0.8562)	0.1973 (1.1129)
L-curve + ICCV	**2.4724**	0.1011 (0.3777)	0.0112 (0.0606)	**0.1017 (0.3781)**	0.1774 (0.9824)	0.0320 (0.1821)	**0.1802 (0.9877)**

3. Refinement of RPC Model

- Motivation
  – Absolute geolocation errors inherently exist in RD model and derived RPC model
  – Such errors may cause significant geometric errors in geocoded SAR images
  – Usually such errors can be described by an affine transformation or even a constant 2D (azimuth and range) offset vector

- Approaches for model refinement
  - in flat terrain:
    - identify GCPs with GPS, DOM, DLG or optical imagery to establish the affine transformation
    - easy to implement
  - in rough terrain (hilly/mountainous areas):
    - difficult to manually identify GCPs
    - simulate SAR image from a reference DEM (SRTM, ASTER GDEM, etc.)
    - use image matching between real and simulated SAR images to identify tie-points for model refinement

- SAR simulation from DEM

azimuth/range sampling spacing

constant

$$DN = k * \sqrt{\sigma} = k * \sqrt{A * \sigma_0} = k * \cos\eta * \sqrt{r_{azi} * \left| \frac{g_h + r_{rng} * \cos\theta}{\sin\theta} \right|}$$

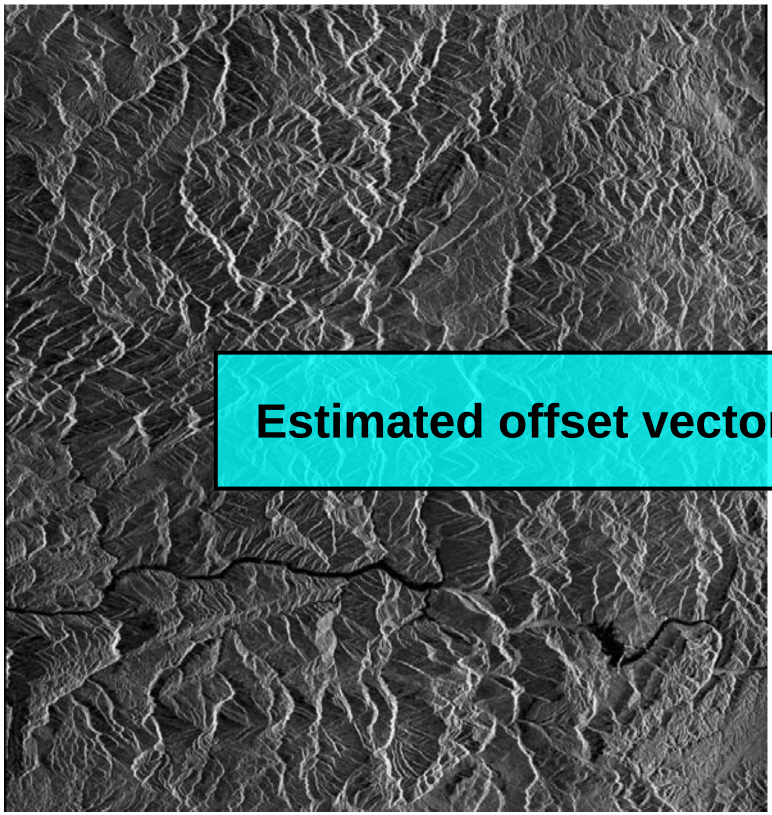
local incidence angle

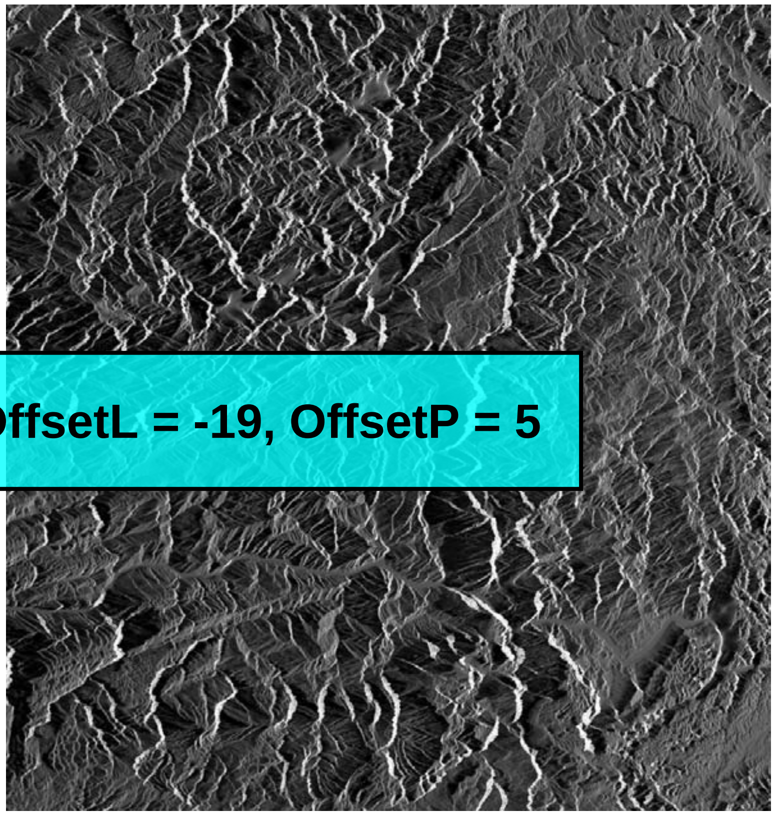
local range elevation gradient

sensor look angle

- Real-simulated image matching
  - two-level matching strategy: first on multi-looked images, then on single look images
  - overall offset vector determined using statistical analysis of identified tie-points

Example of SAR simulation





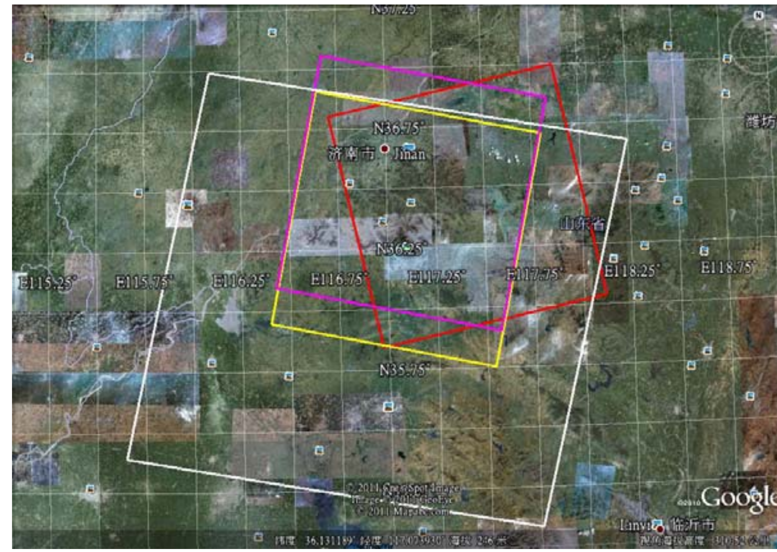
Estimated offset vector: OffsetL = -19, OffsetP = 5

Real SAR ML image (ENVISAT ASAR)

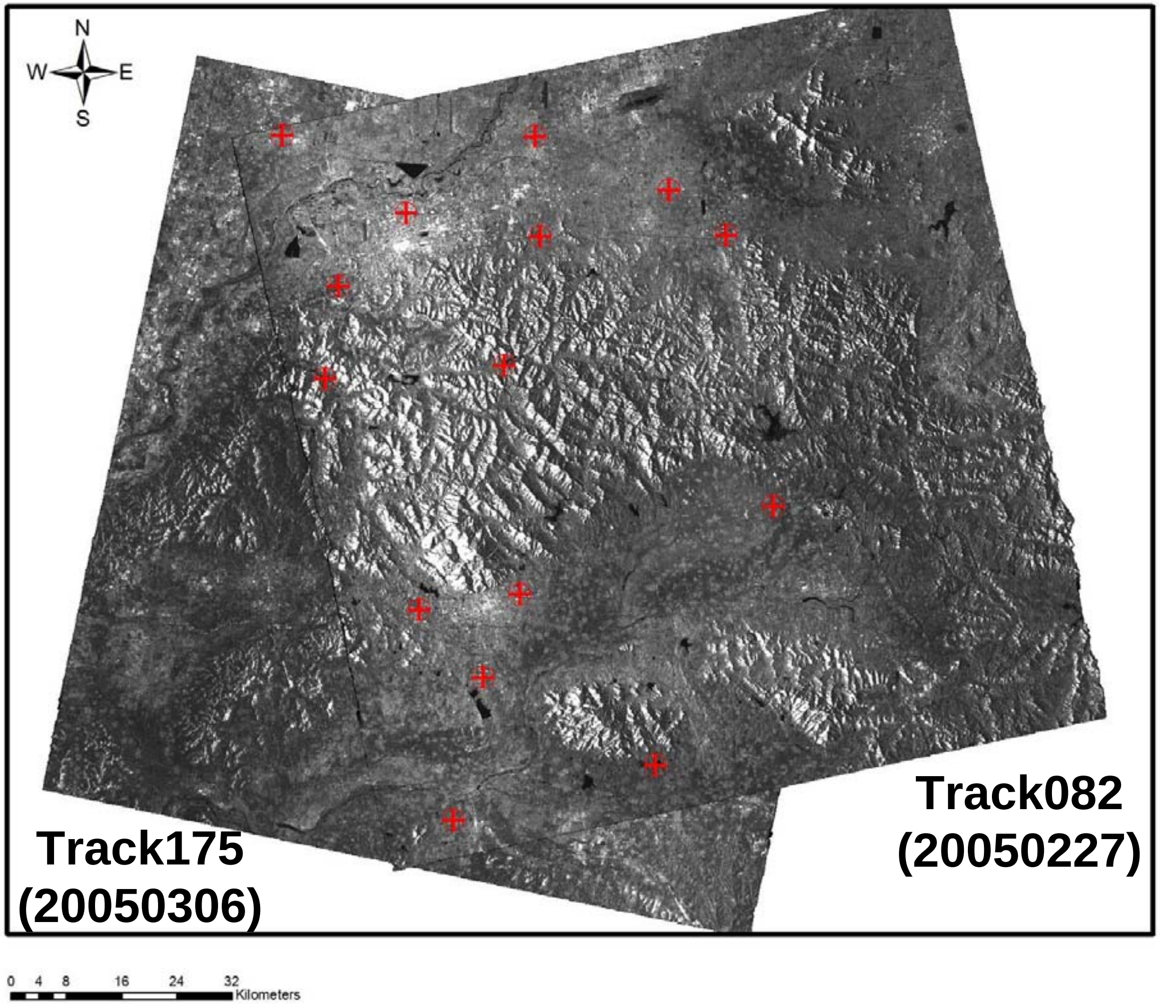
Simulated SAR ML image from SRTM DEM

Experiments

- Study area and datasets
  - Tai'an (Mt.Tai), East China
  - ENVISAT ASAR IMS
  - Landsat-5 TM
  - ASTER GDEM

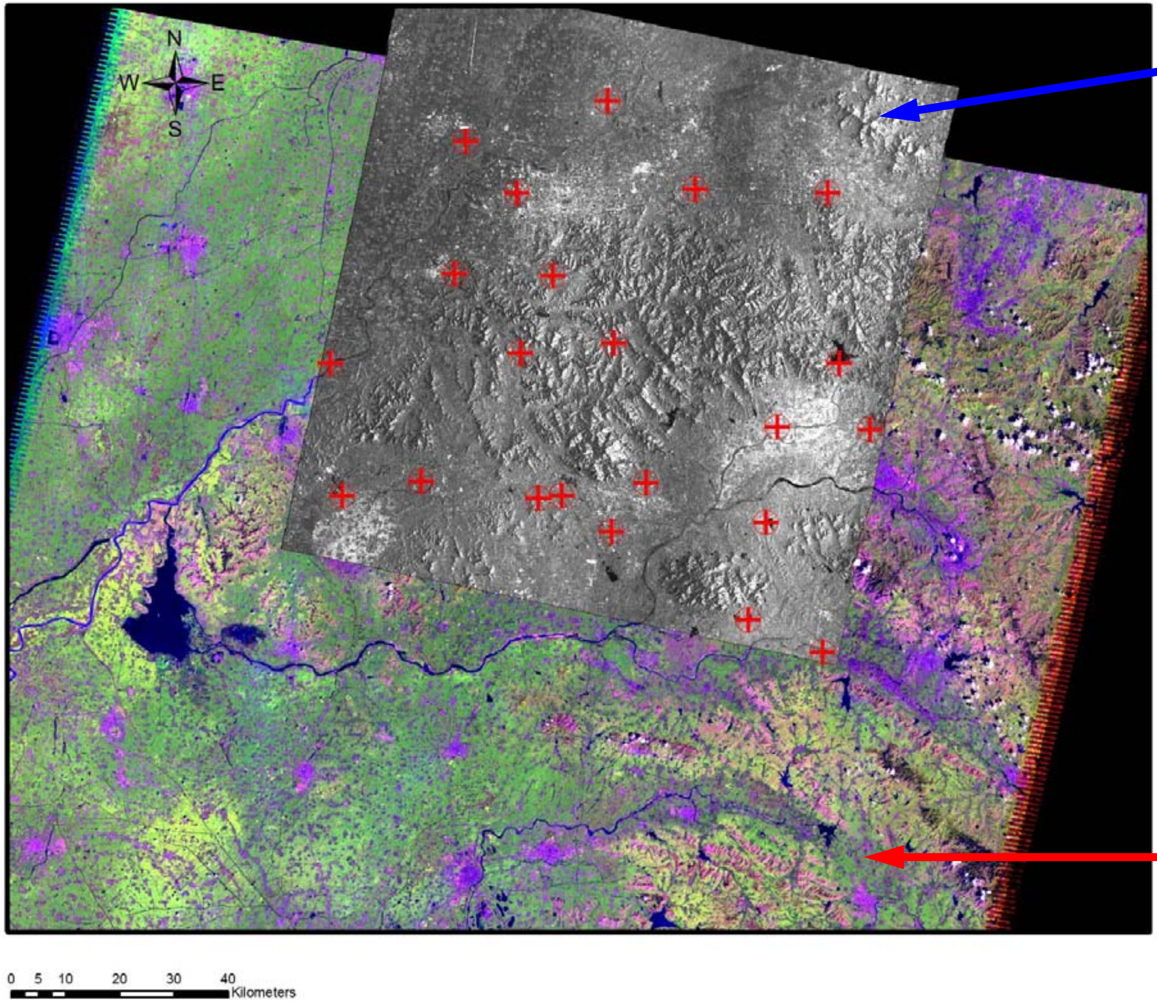


- Objective: accuracy assessment of SAR geocoding with refined RPC model



scenario 1:

Distribution of 15 tie-points within the overlap of ascending-descending ASAR image pair



Track175 (20090906)

scenario 2:

Distribution of 22 tie-points within the overlap of the ASAR and orthorectified Landsat5 TM images

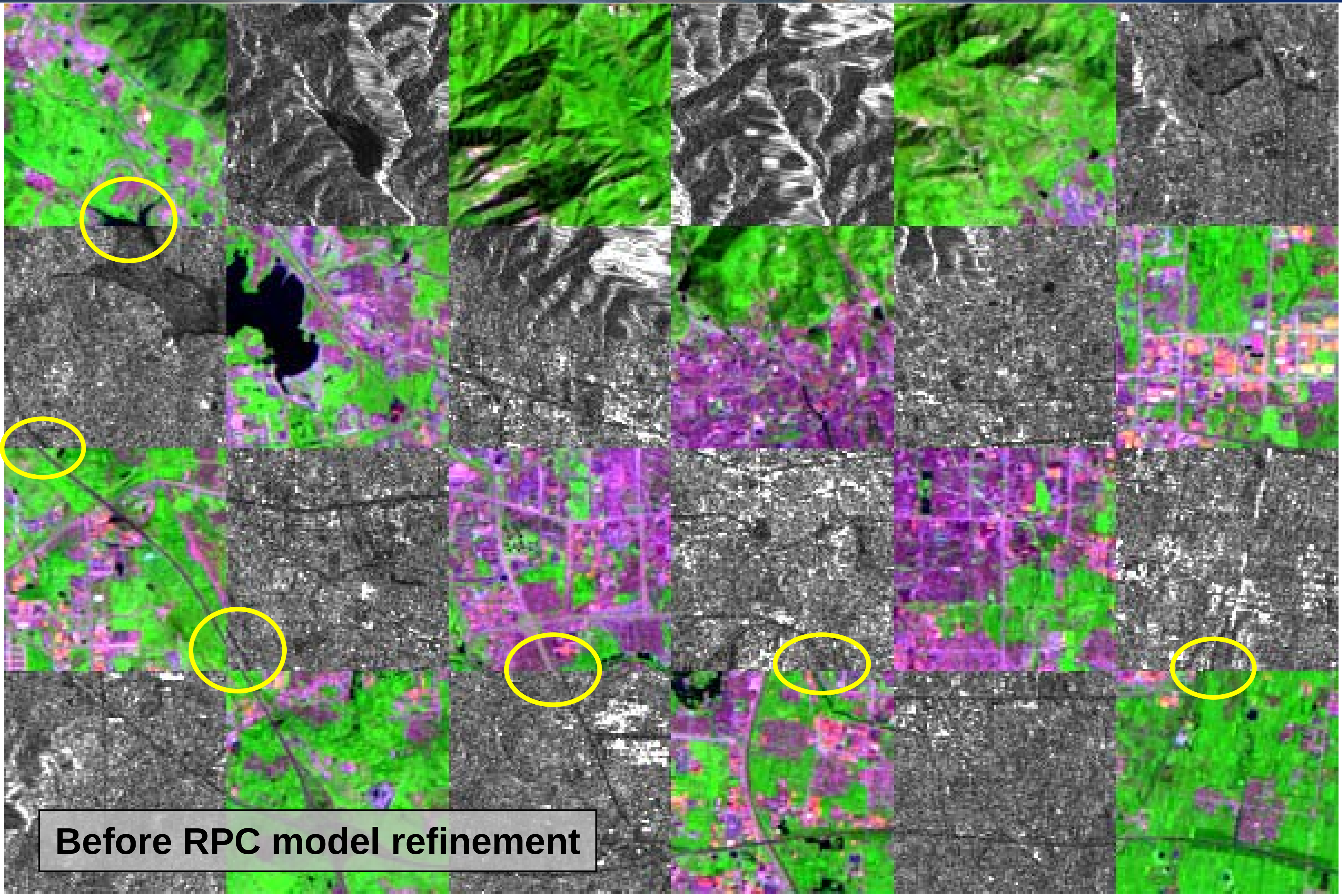
Landsat5 TM (20090830)

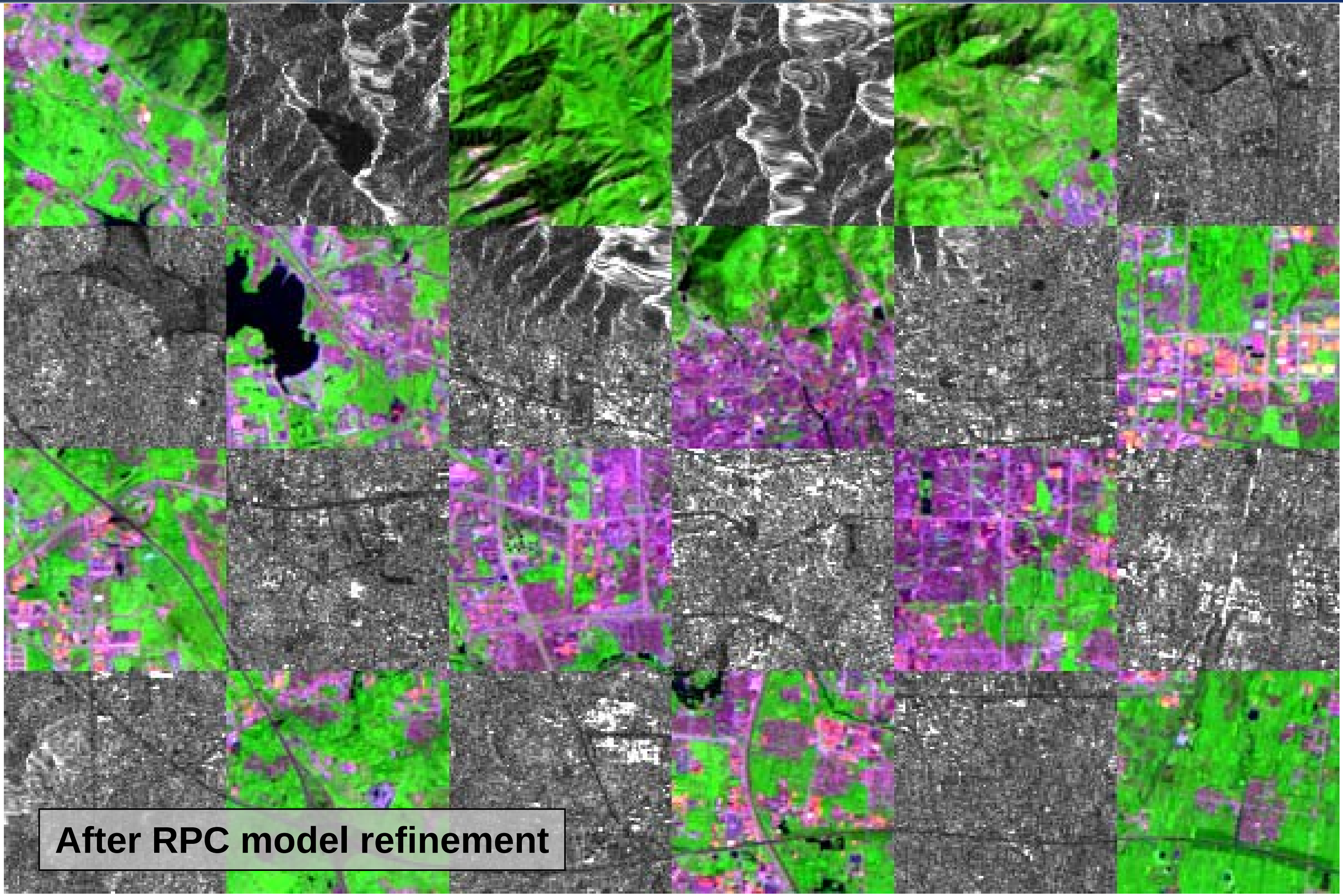
– Estimated geolocation errors

coordinate system: UTM/WGS84 (Zone 50N)

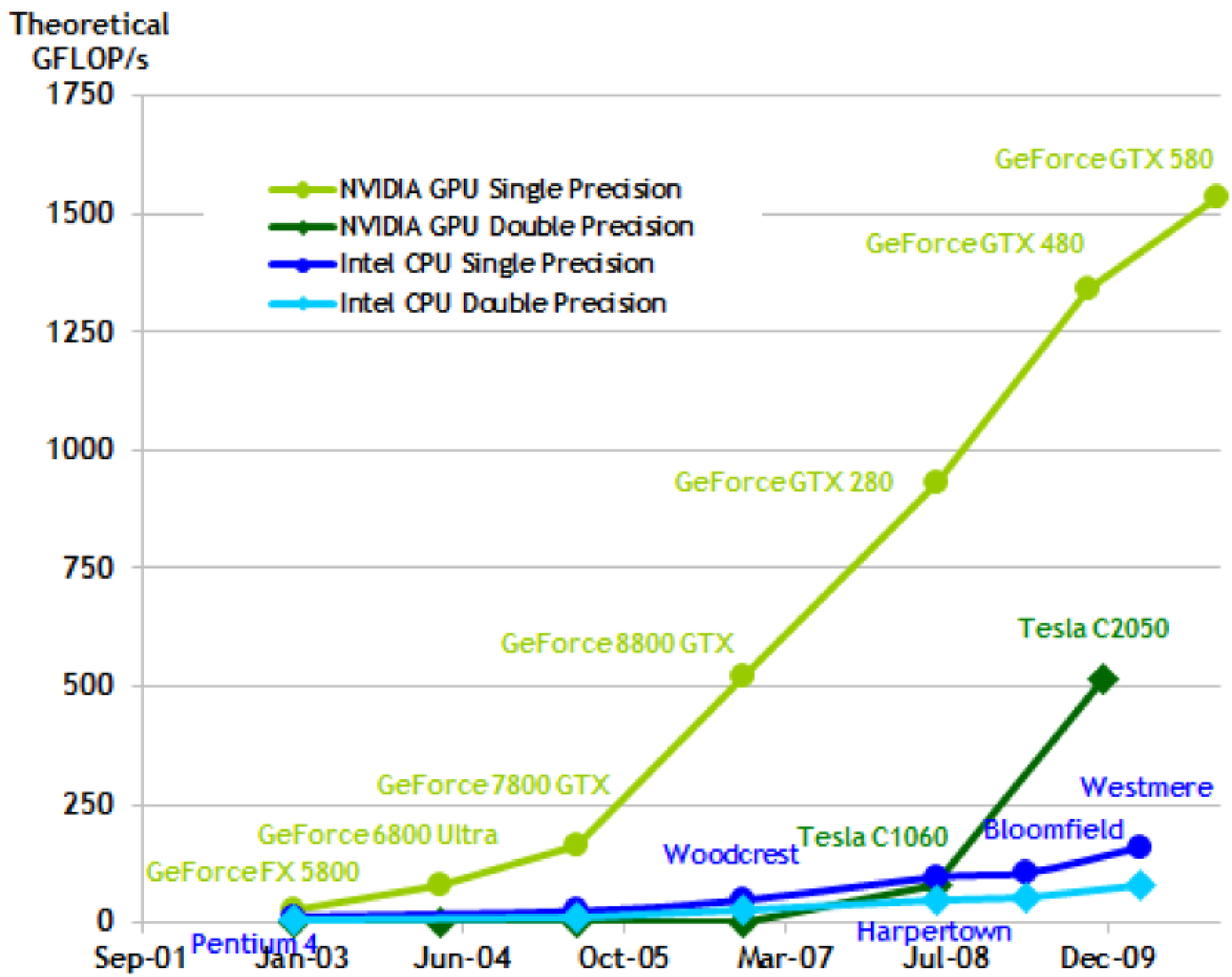
unit: meter

RMSE (STDE)	Geocoding with ordinary RPC model		Geocoding with refined RPC model	
	Delta_X	Delta_Y	Delta_X	Delta_Y
Scenario 1	222.10 (36.43)	18.90 (17.59)	24.09 (24.03)	9.45 (9.45)
Scenario 2	127.64 (26.23)	37.20 (26.36)	21.43 (15.31)	21.35 (19.54)

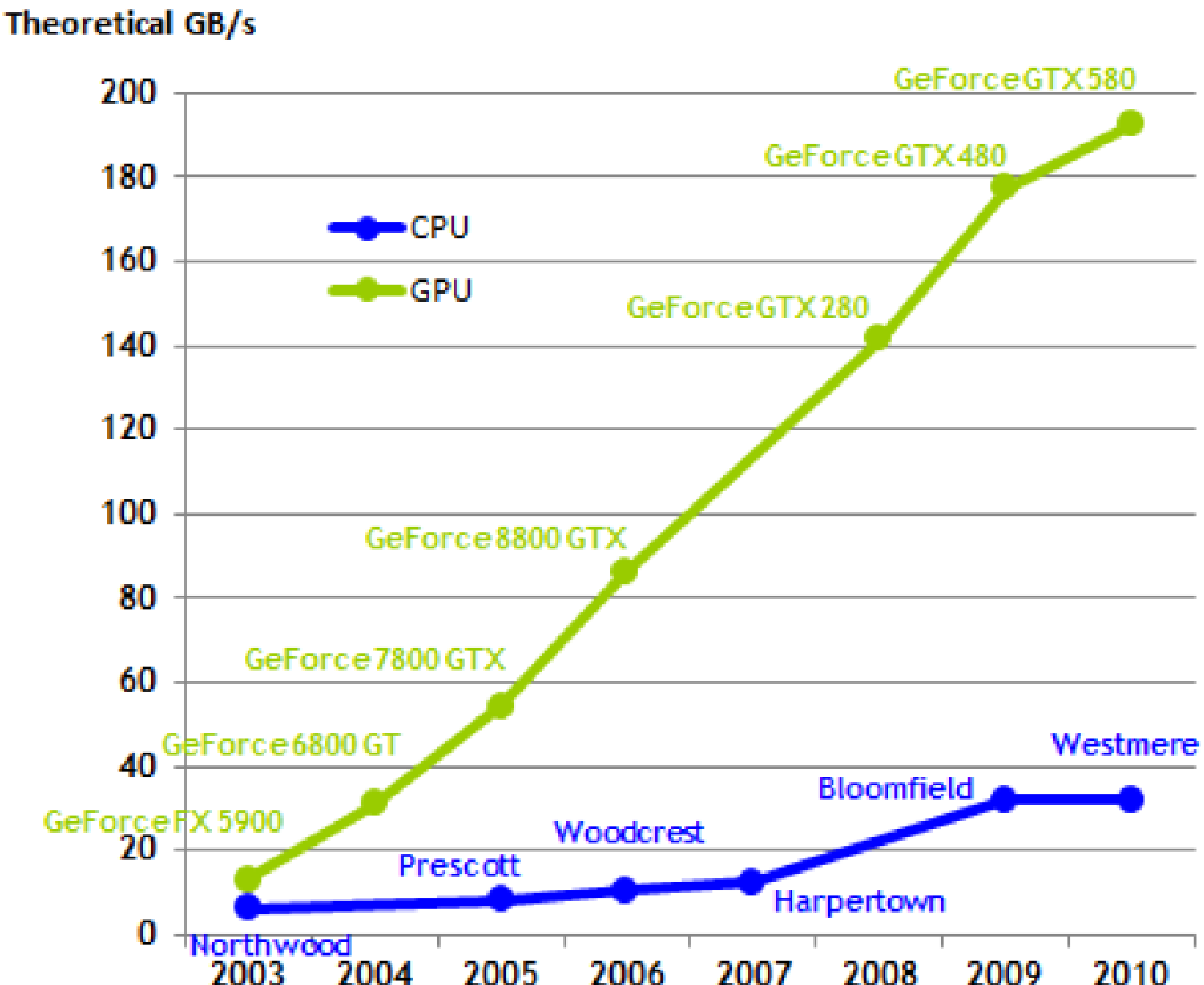

Before RPC model refinement


After RPC model refinement

4. GPU-based Parallel Implementation of SAR Geocoding



(source: CUDA Programming Guide 4.0)



(source: CUDA Programming Guide 4.0)

2048 x 2048 pixel	RD on CPU	RD on CPU (parallel)	RD with CUDA (single precision)	RD with CUDA (double precision)	RD with CUDA (double precision & optimized)
Mean error in pixel	0	1.23E-11	0.562	1.53E-10	2.89E-10
Maximum error in pixel	0	3.12E-09	1.576	3.13E-09	3.15E-09
Calculation time in ms	188 442	111 004	7 651	8 421	7 168
Speedup	1.0	1.7	24.6	22.4	26.3

2048 x 2048 pixel	RPC on CPU	RPC on CPU (parallel)	RPC with CUDA (single precision)	RPC with CUDA (double precision)
Mean error in pixel	0.00012	0.00012	0.03392	0.00012
Maximum error in pixel	0.0007	0.0007	0.08917	0.0007
Calculation time in ms	1409	780	130	260
Speedup	1.0 (133.8)	1.8 (241.6)	10.8 (1449.6)	5.4 (723.9)

SAR image geocoding (including I/O)

Complete scene 5670 x 4774 pixel	RD on CPU	RPC on CPU	RD with CUDA	RPC with CUDA
Calculation time in s	683	43	72	25
Speedup	1.0	15.9	9.5	27.3

Conclusions

- RPC model can be utilized as a reliable replacement of RD model in geometric processing of SAR data
- For areas of rough terrain, RPC model could be refined using real-simulated image matching
- With refined RPC model, absolute location errors in geocoded SAR image can be reduced to within one pixel.
- With massively parallel programming, SAR geocoding in real-time using RPC is possible

Thank You !