Surface Modelling of CO_2 Concentrations based on Flight Test of TanSat Instruments

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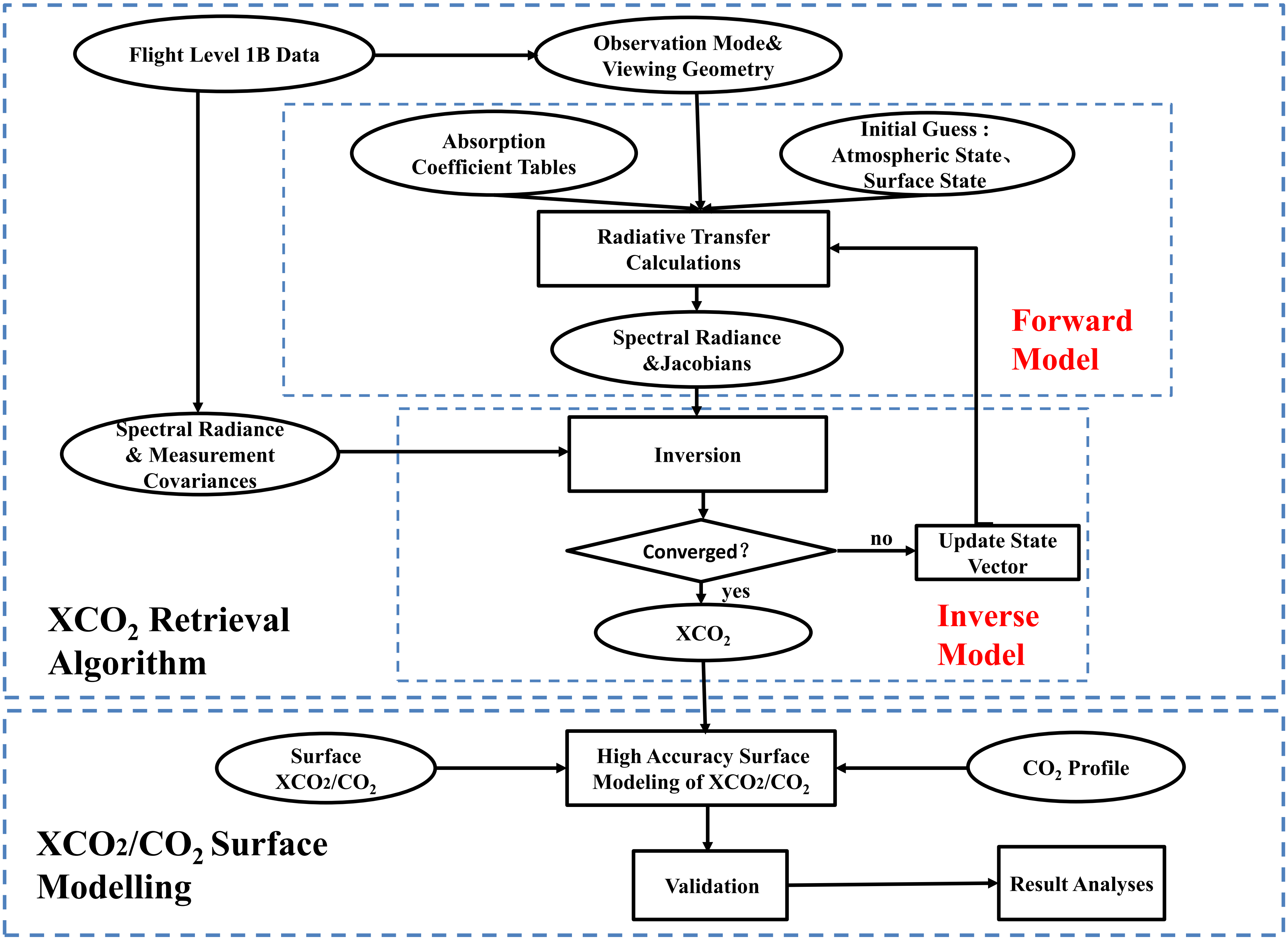
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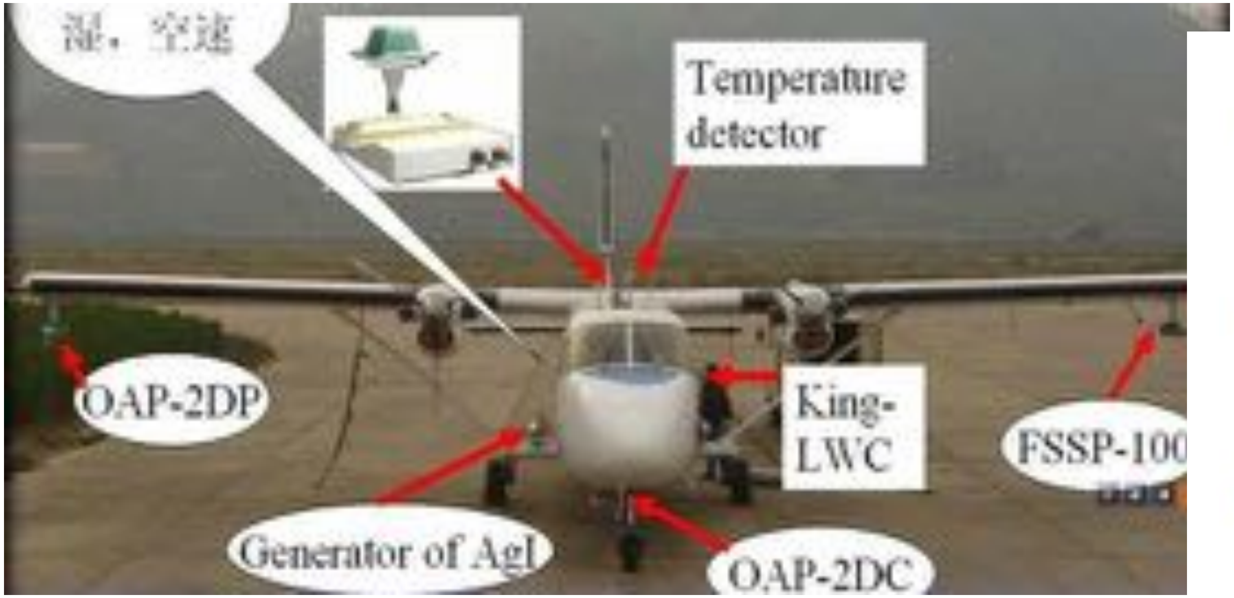
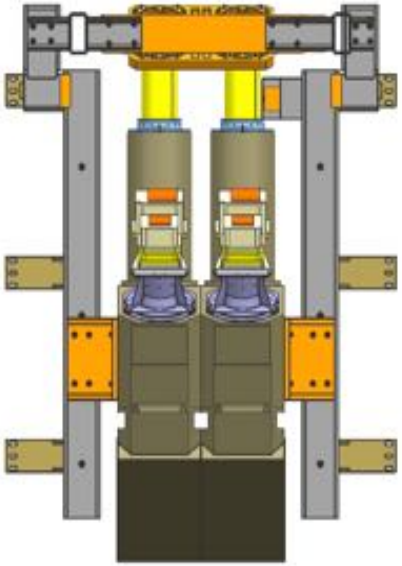
1. The flight test

- **Fixed wing aircraft, Y-12 B-3843;**
- **Maximum flying speed, 350 km per hour;**
- **Highest height, 7000 m;**
- **Longest flying distance, 1340 km;**





1. The flight test

Forward model

Fundamental Equation of atmospheric radiative transfer

$$\mu \frac{dI(\tau,\mu)}{d\tau} = I(\tau,\mu) - J(\tau,\mu)$$

μ: cosine of zenith angle

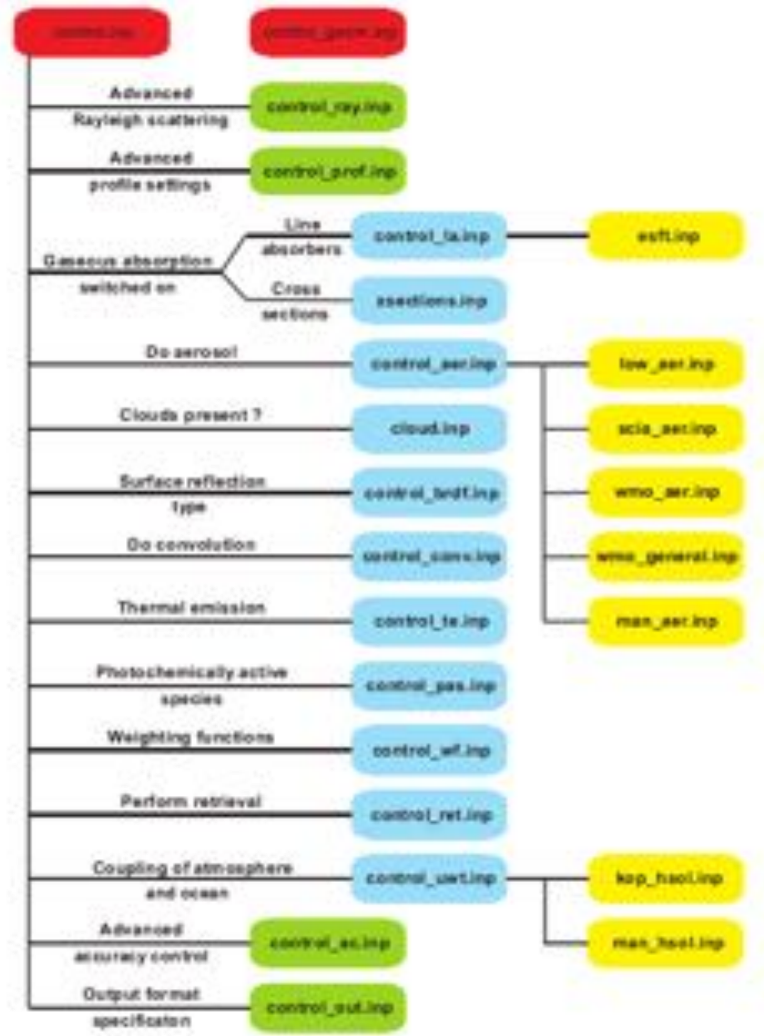
I: specific intensity

J: source function (multiple scattering)

τ: optical depth

SCIATRAN model ⟹

--- (University of Bremen, Germany)



1. The flight test

Inverse model

- Measurement Description

$$\mathbf{y} = f(\mathbf{x}) + \varepsilon$$

y: measurement vector   x: state vector   *f*(x): forward model   ε: measurement error

- Cost Function

$$\chi^2 = [\mathbf{y} - f(\mathbf{x})]^T \mathbf{S}_\varepsilon^{-1} [\mathbf{y} - f(\mathbf{x})] + (\mathbf{x} - \mathbf{x}_a)^T \mathbf{S}_a^{-1} (\mathbf{x} - \mathbf{x}_a)$$

x_a: *a priori* state vector S_ε: measurement error covariance S_a: *a priori* error covariance

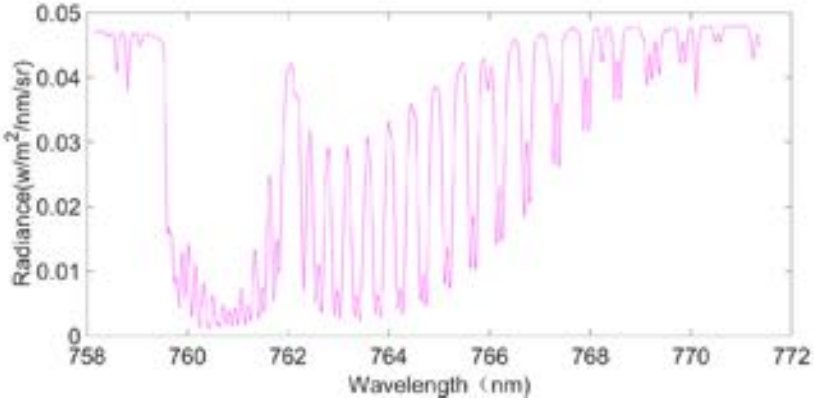
- Levenberg-Marquardt method

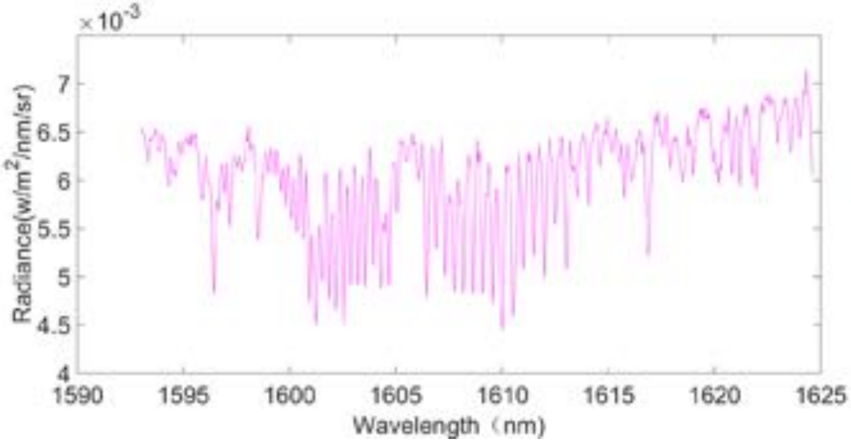
$$\mathbf{x}_{i+1} = \mathbf{x}_i + [(1+\gamma_i)\mathbf{S}_a^{-1} + \mathbf{K}_i^T \mathbf{S}_\varepsilon^{-1} \mathbf{K}_i]^{-1} [\mathbf{K}_i^T \mathbf{S}_\varepsilon^{-1} (\mathbf{y} - f(\mathbf{x}_i)) - \mathbf{S}_a^{-1} (\mathbf{x}_i - \mathbf{x}_a)]$$

dx: state vector update   K: weighting function (Jacobian)   γ: Levenberg-Marquardt parameter

—(Rodger, 2000)

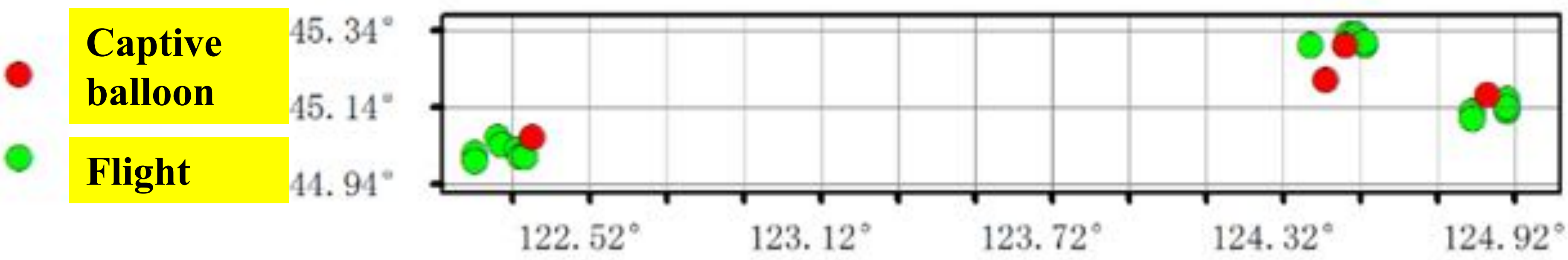
1. The flight test

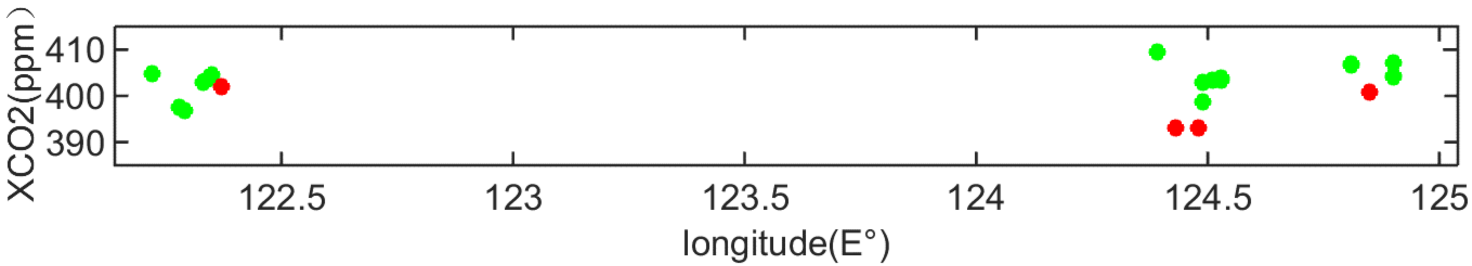




	Wave band 1	Wave band 2
Wavelength range (nm)	758-772	1592-1625
Spectral resolution（nm）	0.044	0.13

1. The flight test





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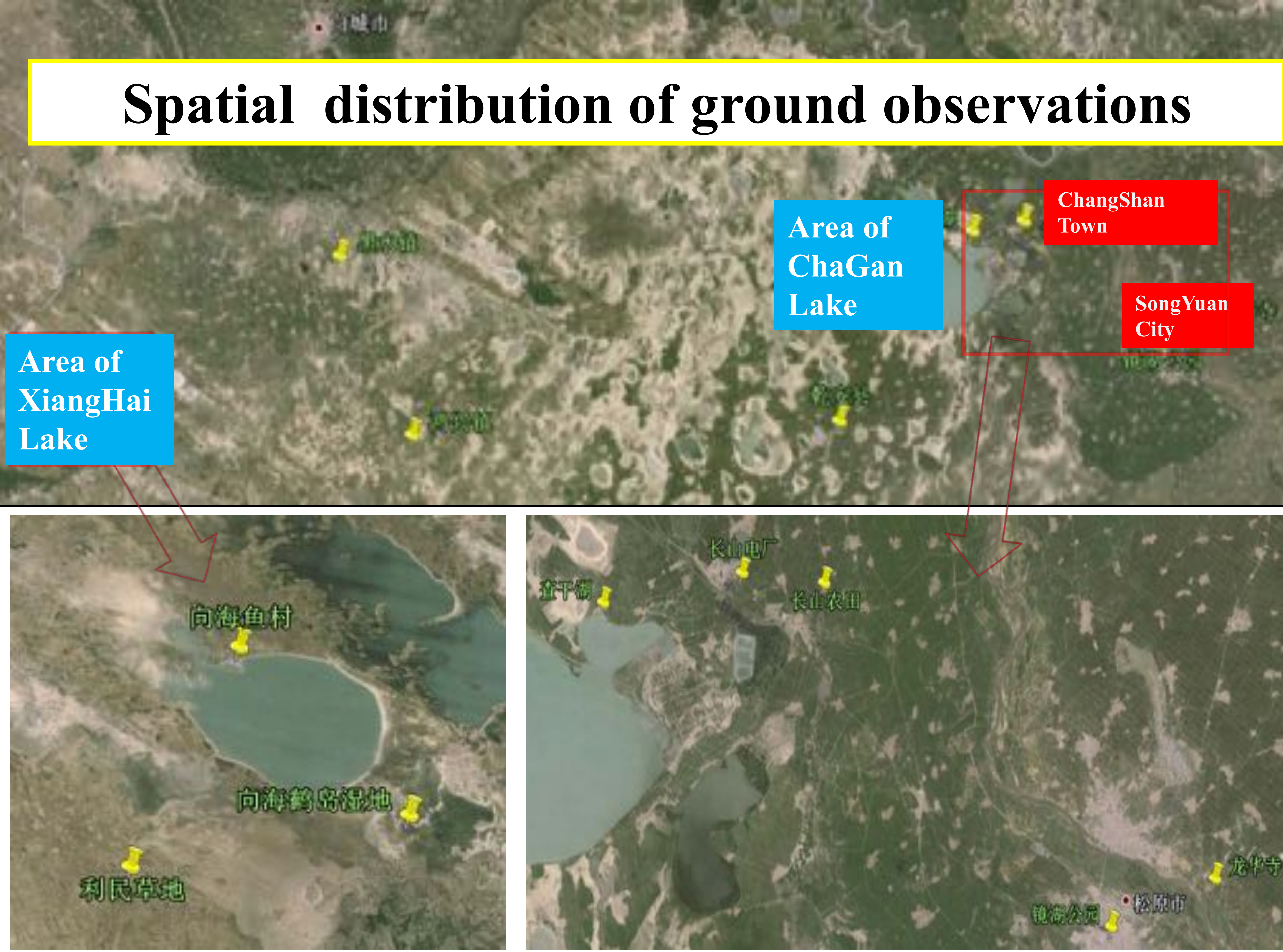
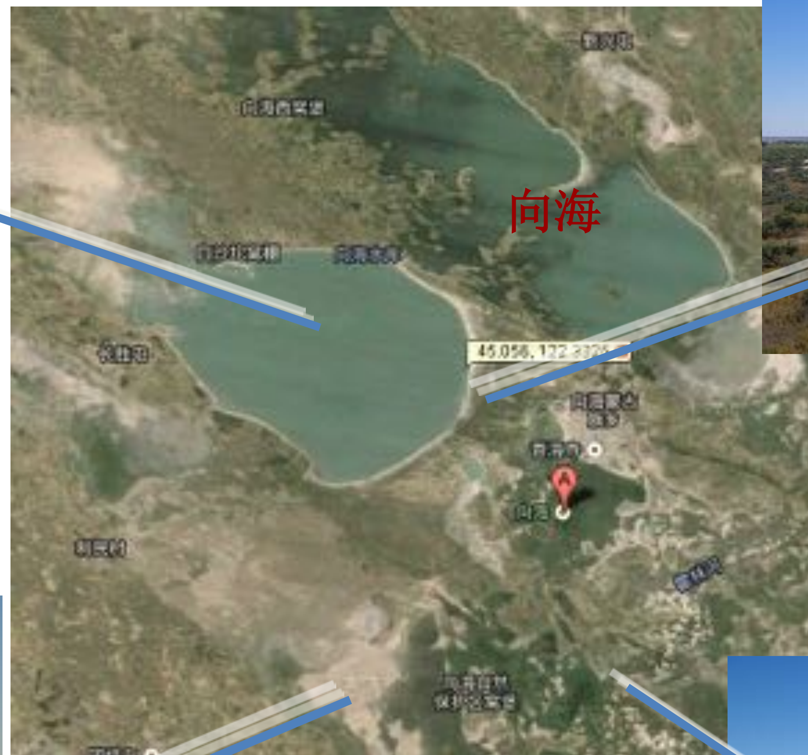
Spatial distribution of ground observations



2. Ground observations

Water body



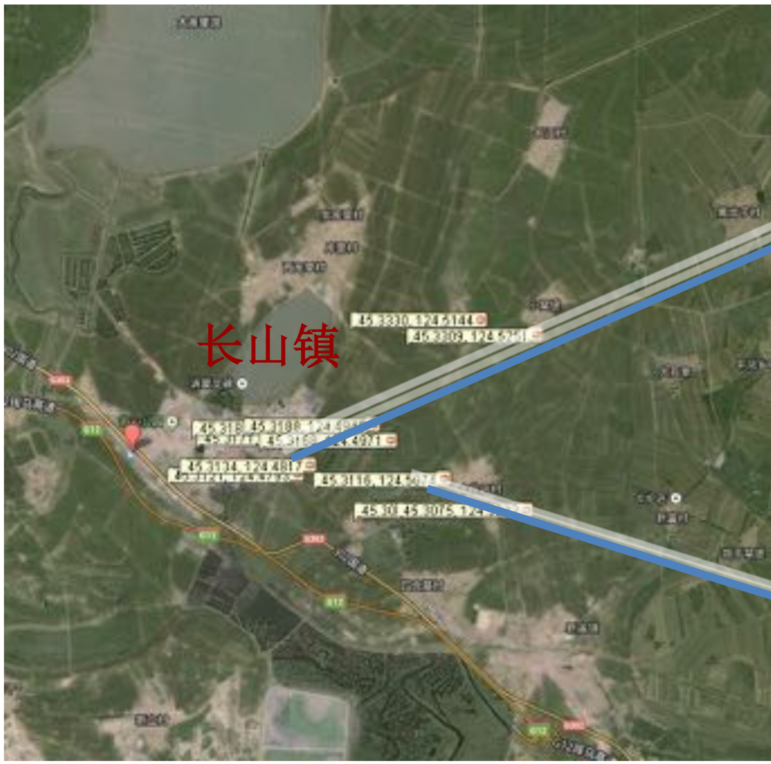
Area of XiangHai Lake

Shrub land

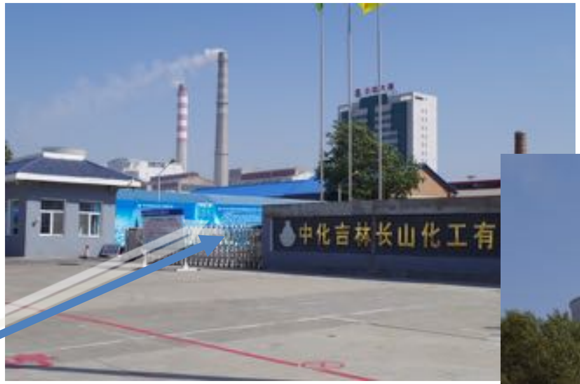
Grassland

Wetland

2. Ground observations



ChangShan Town



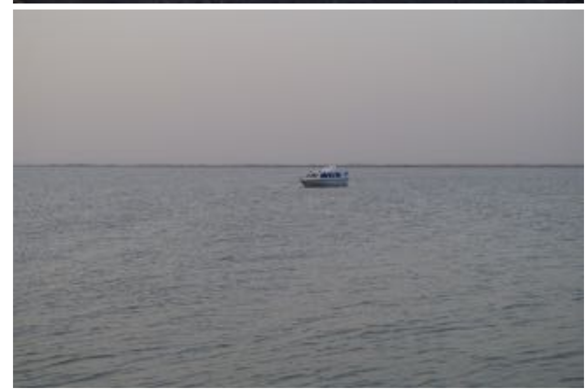
Chemical Plant

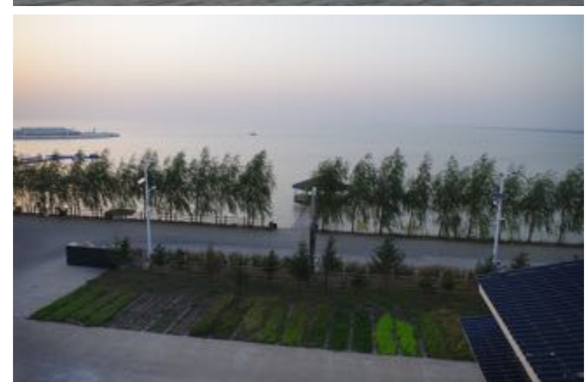
Thermal Power Plant

Farmland

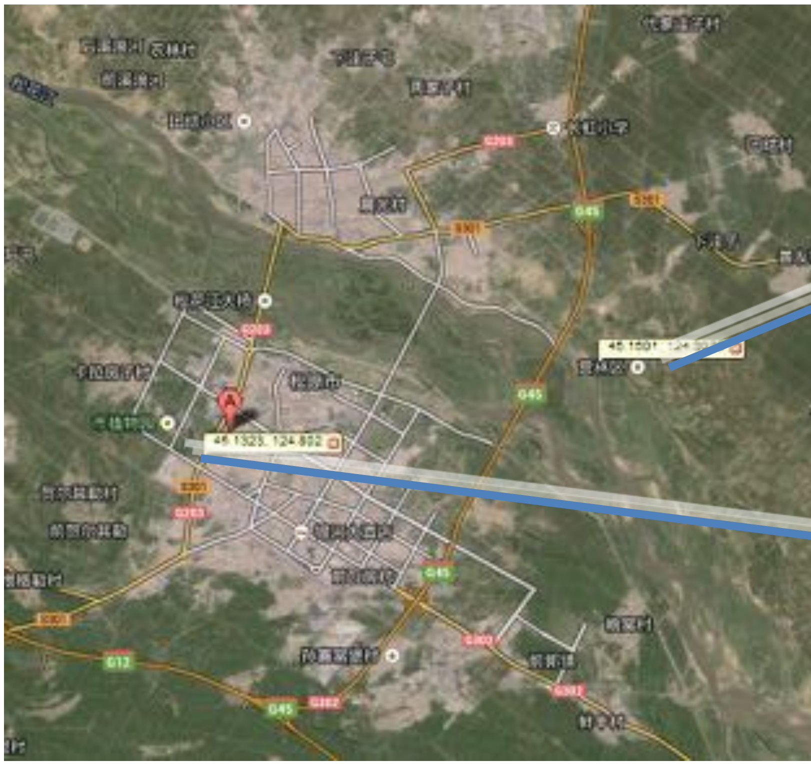
2. Ground observations

Area of ChaGan Lake





2. Ground observations



SongYuan City

LongHua Forest Garden

JingHu Lake Garden

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3. A Method for surface modelling

In terms of the fundamental theorem of surfaces, a surface is uniquely defined by the first fundamental coefficients and the second fundamental coefficients.

Ref.

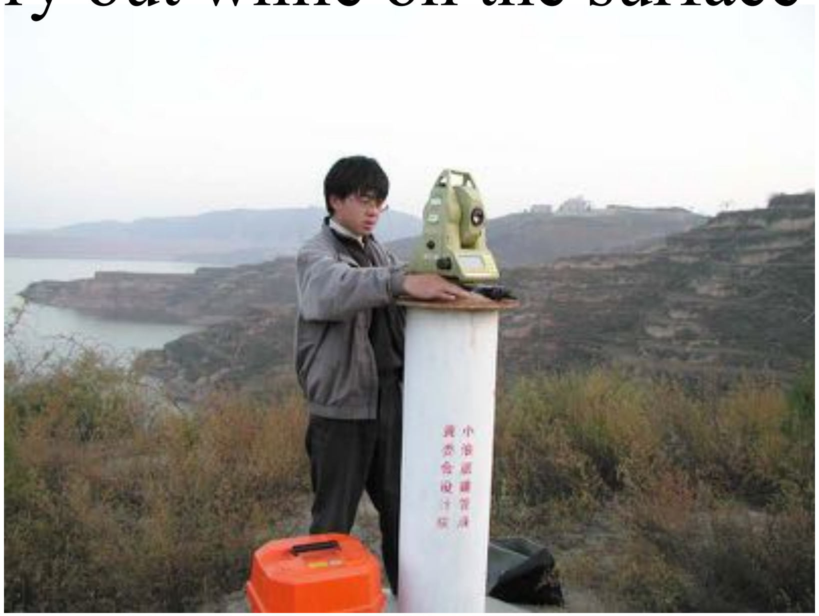
- **TianXiang Yue, ZhengPing Du, DunJiang Song et al. 2007. Geomorphology 91(1-2): 161-172.**
- **TianXiang Yue, DunJiang Song, ZhengPing Du, et al. 2010. International Journal of Remote Sensing 31 (8): 2205-2226.**
- **Tian-Xiang Yue, Shi-Hai Wang. 2010. International Journal of Geographical Information Science 24 (11): 1725 - 1743.**
- **Tian-Xiang Yue, Chuan-Fa Chen, Bai-Lian Li. 2010. Transactions in GIS 14 (5): 615-630.**

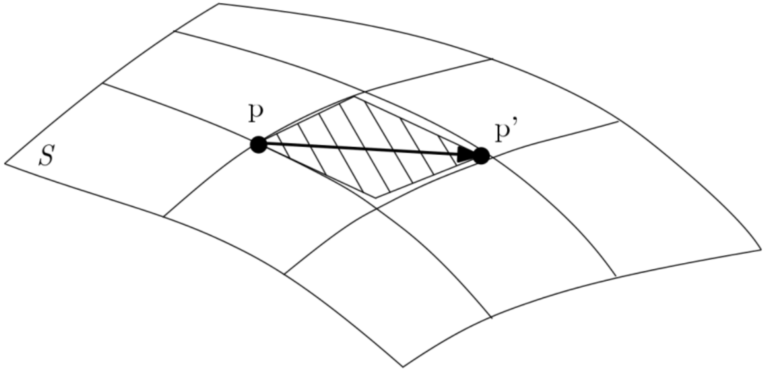
3. A Method for surface modelling

The first fundamental coefficients are used to express the intrinsic geometric properties that do not depend on the shape of the surface, but only on measurements that we can carry out while on the surface itself.

$$z = f(x, y)$$

$$\begin{cases} E = r_x \cdot r_x = 1 + f_x^2 \\ F = r_x \cdot r_y = f_x f_y \\ G = r_y \cdot r_y = 1 + f_y^2 \end{cases}$$

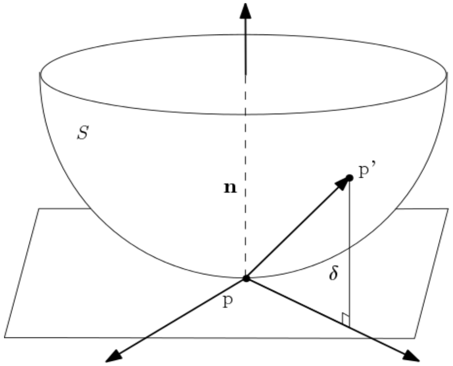




3. A Method for surface modelling

The second fundamental coefficients reflect the local warping of the surface, namely its deviation from a tangent plane at the point under consideration, which can be observed from outside the surface.

$$z = f(x, y)$$



$$\begin{cases} L = r_{xx} \cdot \vec{N} = \dfrac{f_{xx}}{\sqrt{1 + f_x^2 + f_y^2}} \\ M = r_{xy} \cdot \vec{N} = \dfrac{f_{xy}}{\sqrt{1 + f_x^2 + f_y^2}} \\ N = r_{yy} \cdot \vec{N} = \dfrac{f_{yy}}{\sqrt{1 + f_x^2 + f_y^2}} \end{cases}$$

Ref.: Tian-Xiang Yue. 2011. Surface Modelling: High Accuracy and High Speed Methods. New York: CRC Press.
http://www.crcpress.com/product/isbn/9781439817582

3. A Method for surface modelling

High accuracy surface modeling (HASM), taking global approximate information (e.g., remote sensing images or model simulation results) as its driving field and local accurate information (e.g., ground observation data and/or sampling data) as its optimum control constraints.

$$\begin{cases} \min \left\| \begin{bmatrix} A \\ B \\ C \end{bmatrix} \cdot z^{(n+1)} - \begin{bmatrix} d^{(n)} \\ q^{(n)} \\ p^{(n)} \end{bmatrix} \right\| \\ s.t. \\ S \cdot z^{(n+1)} = k \\ l_b < z^{(n+1)} < u_b \\ T_I \cdot z^{(n+1)} \le b_I \end{cases}$$

global approximate information

optimum control constraints

3. A Method for surface modelling

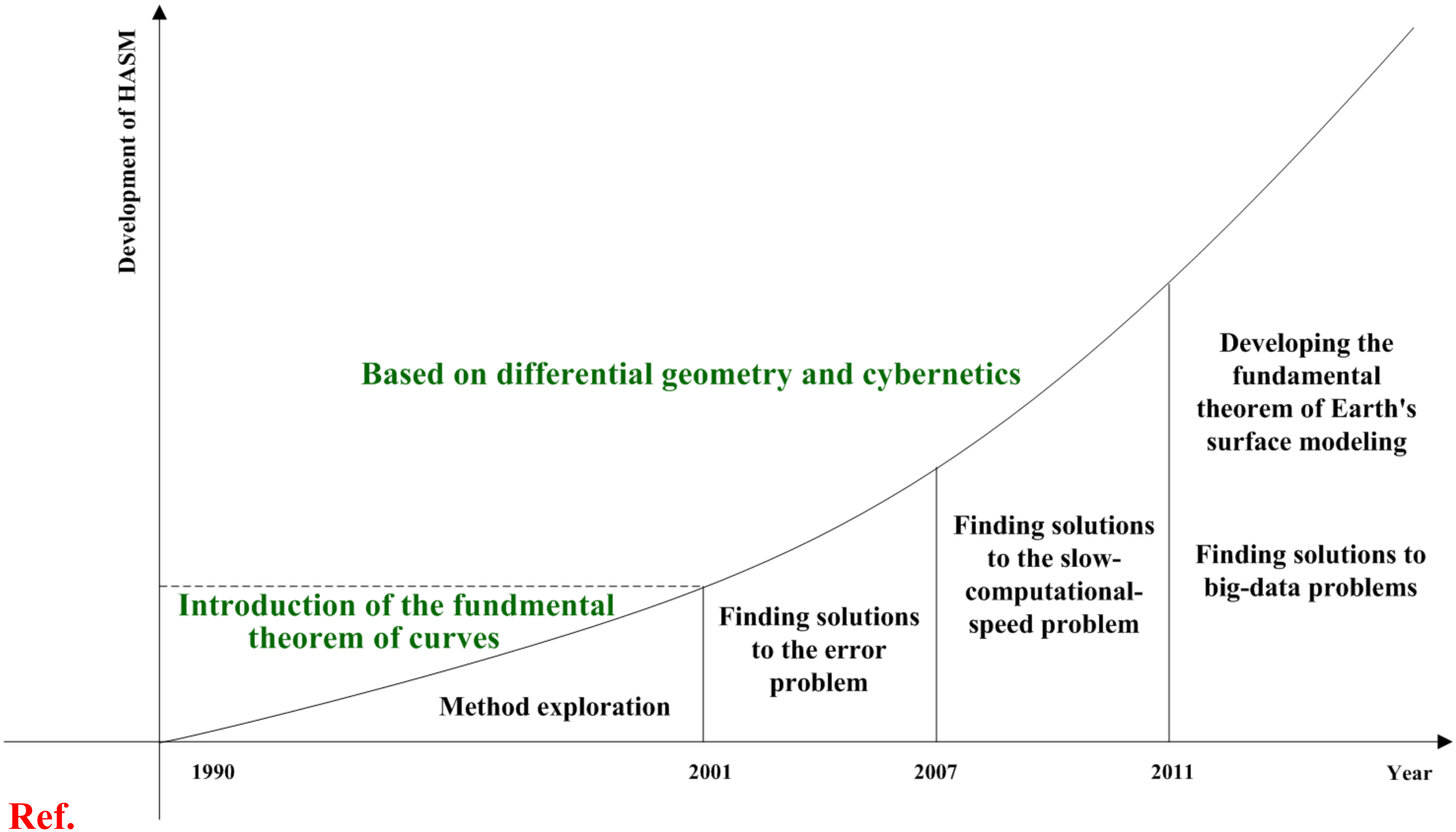
The Fundamental Theorem of Earth's Surface Modelling: **An Earth's surface system or a component surface of the Earth's surface environment can be simulated with HASM when its spatial resolution is fine enough, which is uniquely defined by both extrinsic and intrinsic invariants of the surface.**

From FTESM, seven corollaries have been deduced, corresponding to interpolation, upsaling, downscaling, data fusion and data assimilation respectively

Ref.

- **TianXiang Yue, Yu Liu, MingWei Zhao, ZhengPing Du, Na Zhao. 2016. Environmental Earth Sciences 75(9): article 751 (pages 1 -12).**

3. A Method for surface modelling



Ref.

- **TianXiang Yue, LiLi Zhang, Na Zhao, et al. 2015. Environmental Earth Sciences 74(8), 6541-6549**

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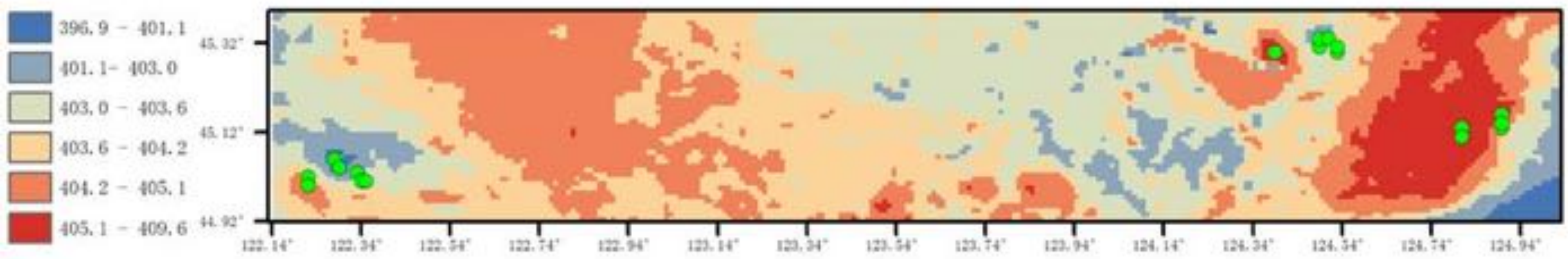
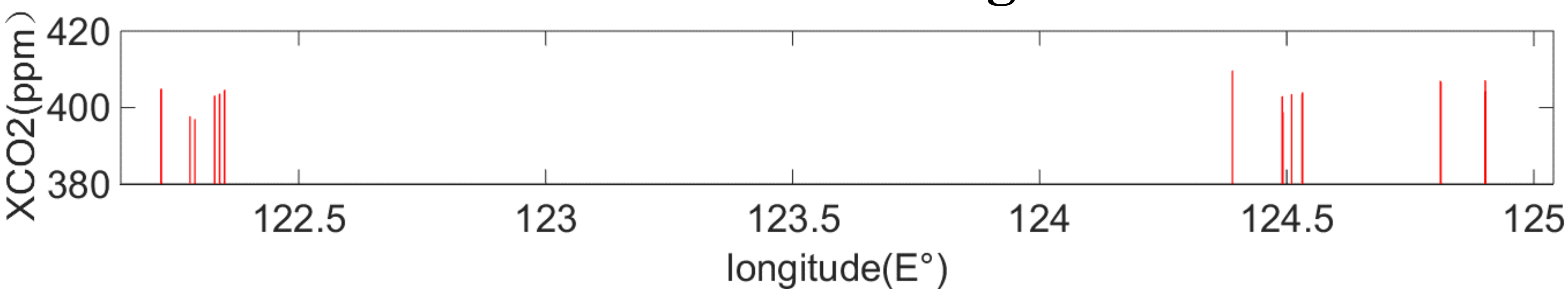
4. Surface modelling of CO_2



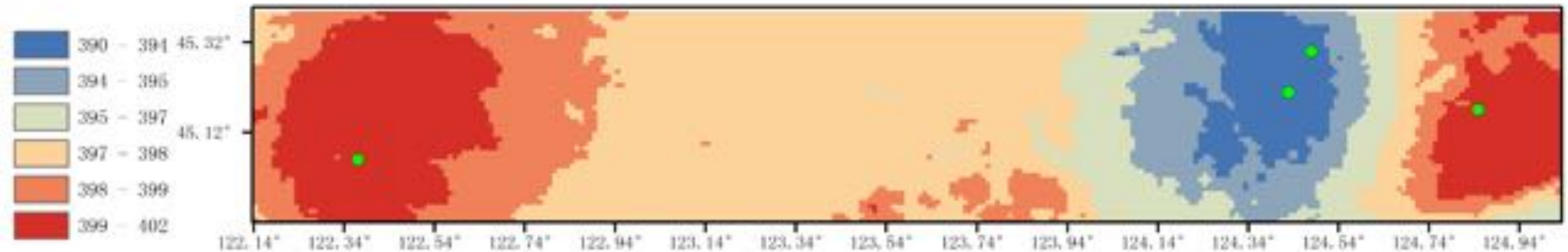
XCO_2 surface based on flight data



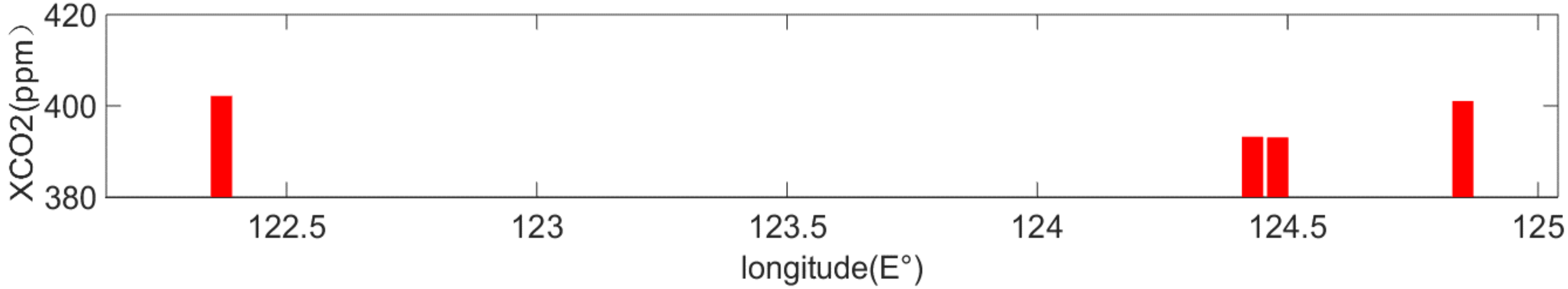
XCO_2 based on flight data

Method	Kriging	IDW	HASM
Mean absolute error (ppm)	1.87	1.99	1.74
Mean relative error (%)	0.46	0.49	0.43

4. Surface modelling of CO_2



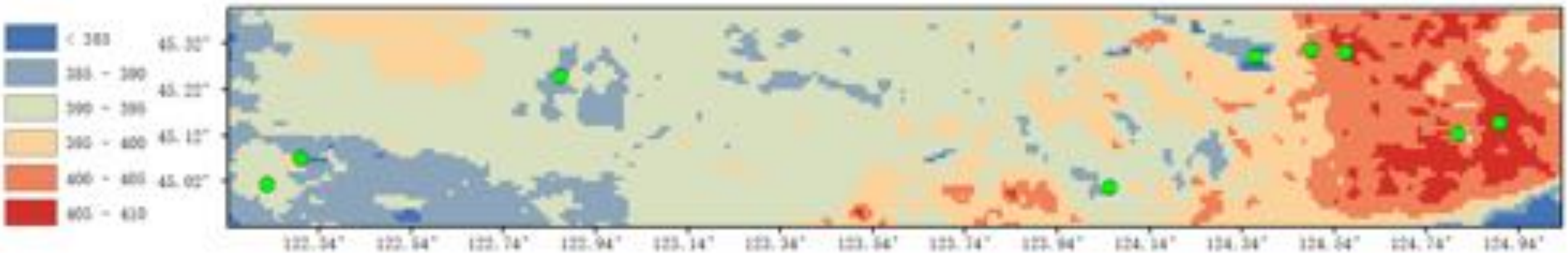
XCO_2 surface based on captive balloon data



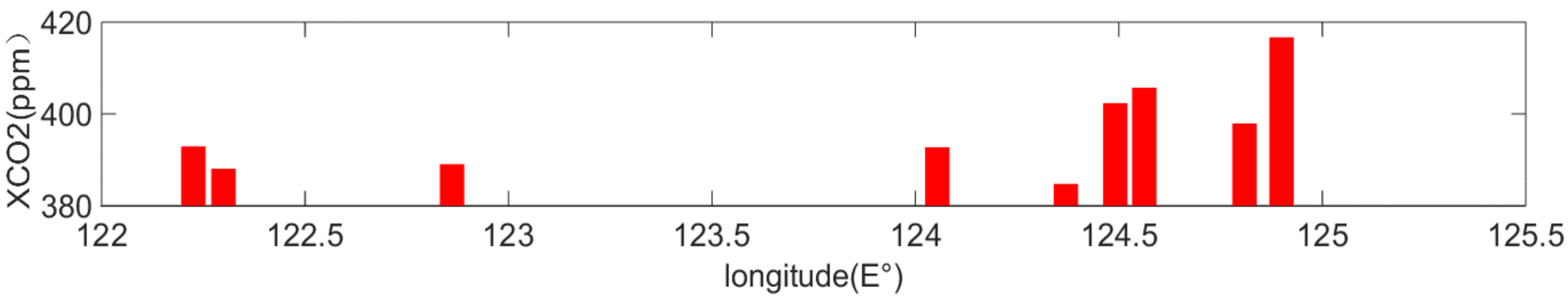
XCO_2 based on captive balloon data

Test area: 220 km×50 km

4. Surface modelling of CO_2



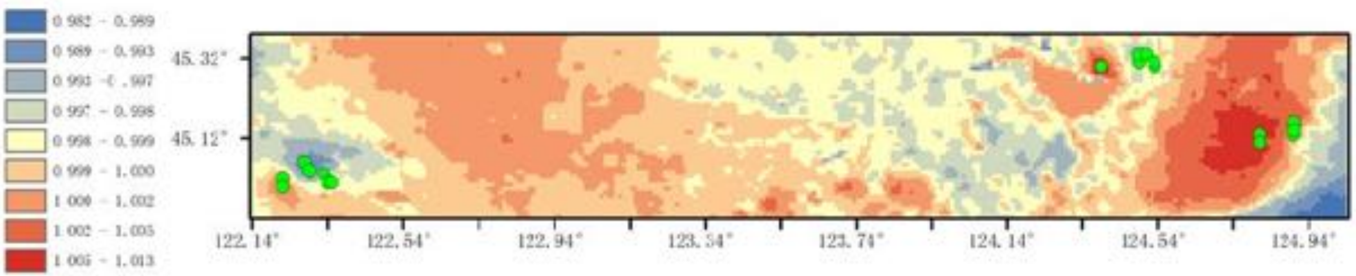
CO_2 surface based on ground observation data



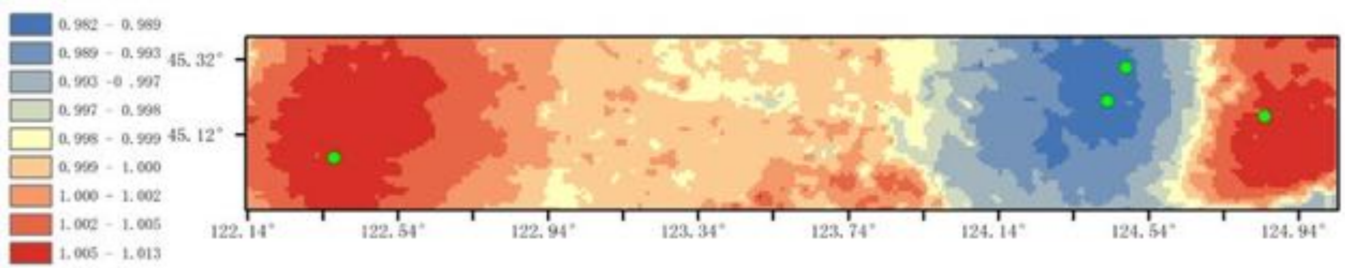
CO_2 based on ground observation

Test area: 220 km×50 km

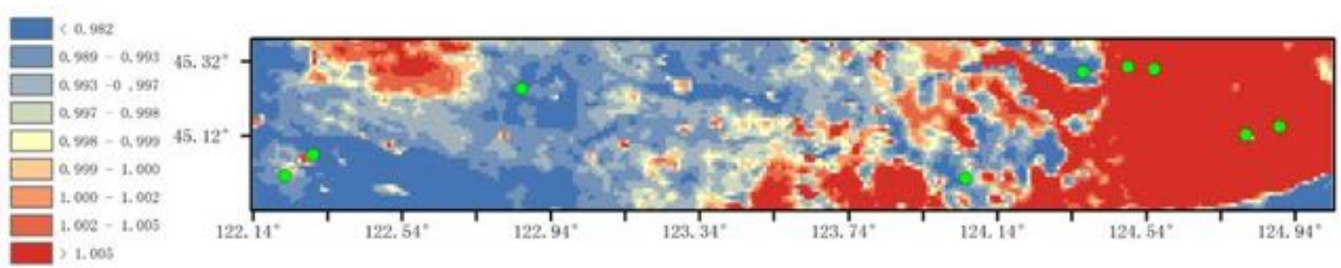
4. Surface modelling of CO_2



Normalized XCO2 surface based on flight data



Normalized XCO2 surface based on captive balloon data



Normalized CO2 surface based on ground observation data

Contents

5. Discussion

① The observation time is not same

- Daily mean XCO2 concentrations from flight data, September 11, 14 and 16, 10:00 to 13:00
- Daily mean XCO2 concentrations from captive balloon data, September 8 - 15, 8：00–14：00
- Daily mean CO2 concentrations from ground observations, September 8 - 17 , whole day

② Different heights

- Flight, 5000 m
- Captive balloon, 0 - 1000 m
- Ground observations, 2 m

5. Discussion

③ Development of various new systems under the Fundamental Theorem of Earth's Surface Modelling

- For spatial interpolation
- For data fusion
- For data assimilation
- For upscalling
- For downscaling

Thank you for your attention!