Высокодетальное распределение NO2 в тропосфере урбанизированных районов по данным гиперспектральной аппаратуры КА Ресурс-П: алгоритм, результаты измерений, валидация с помощью моделей и измерений, оценка выбросов

Постыляков О.В.[1], Боровский А.Н.[1], Шукуров К.А.[1], Макаренков А.А.[2], Давыдова М.А.[31], Мухартова Ю.В.[31]

[1] Институт физики атмосферы им. А.М. Обухова РАН

[2] Рязанский государственный радиотехнический университет

[3] Московский государственный университет им. М.В. Ломоносова

oleg.postylyakov@gmail.com

NOx in troposphere

Troposphere

NO_x are emitted mainly in the form of NO

Large content of free radicals and VOCs in the troposphere leads to appearing of transformation ways of NO to NO_2 without ozone destruction

Ozone generation

$NO + O_3 \rightarrow NO_2 + O_2$

$NO + VOC \rightarrow NO_2 + O_2 + VOC$

$NO + FR \rightarrow NO_2 + O_2 + FR$

$NO_2 + h\nu \rightarrow NO + O$

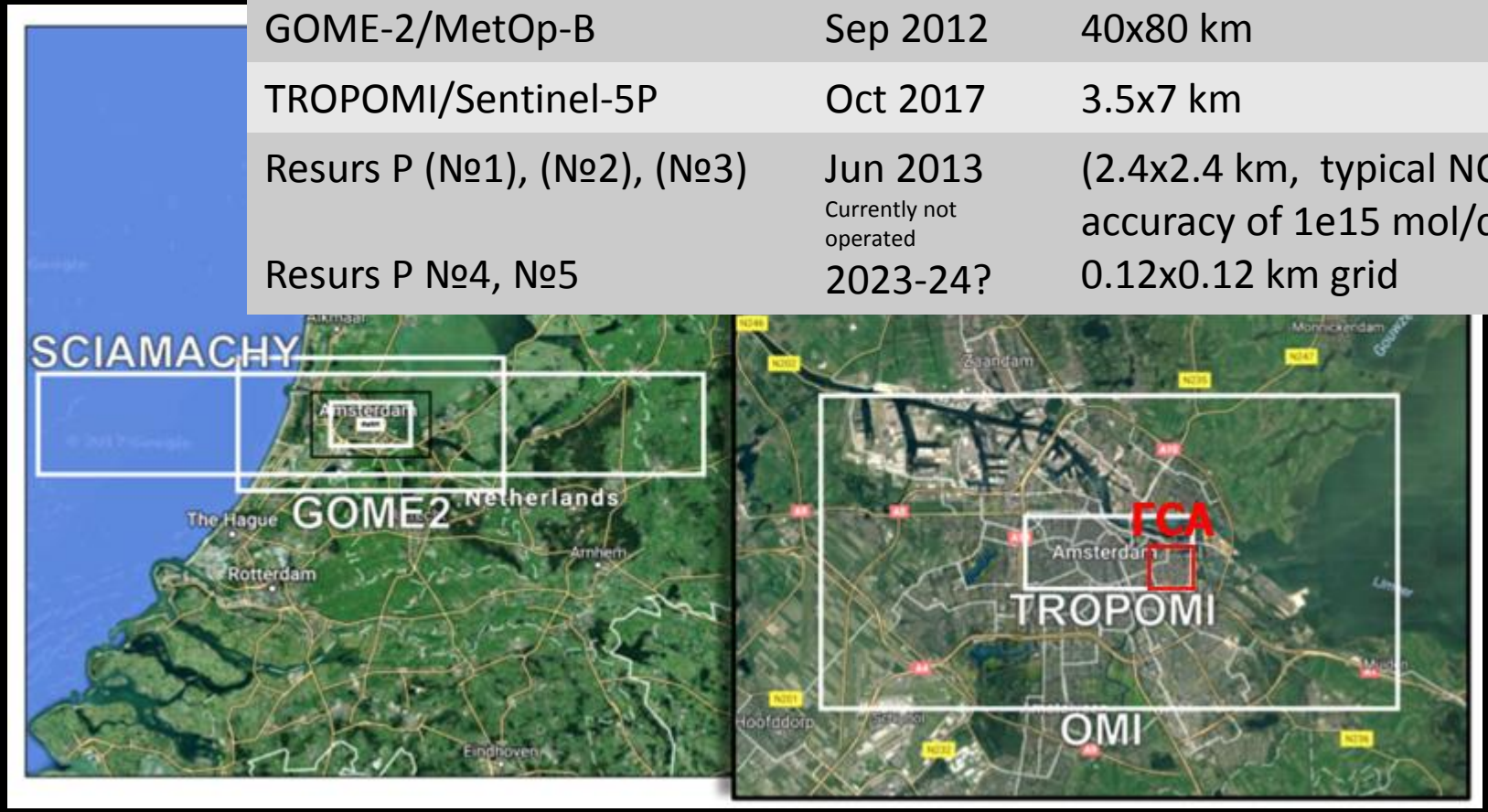
$O_2 + O + M \rightarrow O_3 + M$

VOC – volatile organic compound; FR – free radical

- Chemically important gas
  - ozone generation
  - Indicator of VOCs and free radicals;
- Contribute to radiation balance;
- Impact on ecosystems (degradation of flora and fauna, respiratory illnesses, mutations).

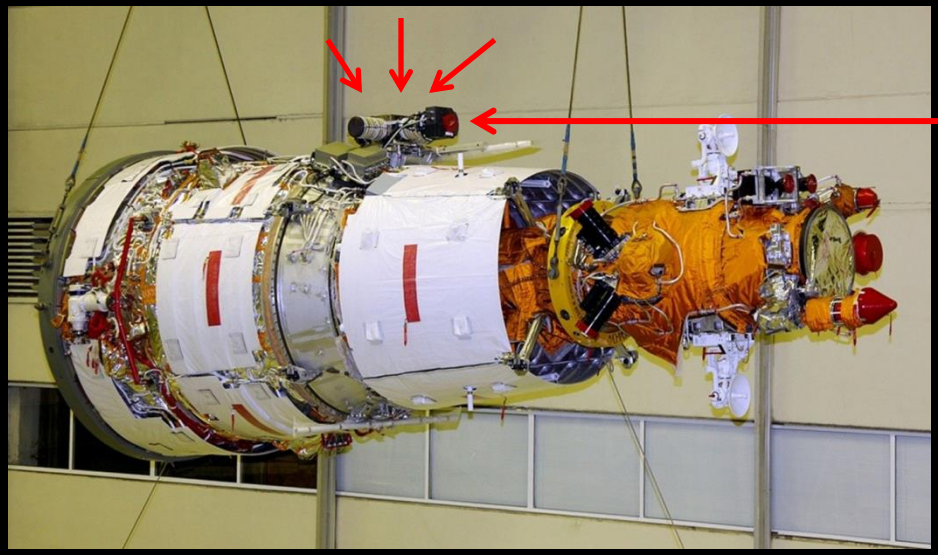
NO2 satellite instruments

Satellite	Launch date	NO2 resolution
OMI/Aura	Jul 2004	13x24 km
GOME-2/MetOp-A	Oct 2006	40x80 km
GOME-2/MetOp-B	Sep 2012	40x80 km
TROPOMI/Sentinel-5P	Oct 2017	3.5x7 km
Resurs P (№1), (№2), (№3)	Jun 2013 Currently not operated	(2.4x2.4 km, typical NO2 VCD accuracy of 1e15 mol/cm2)
Resurs P №4, №5	2023-24?	0.12x0.12 km grid



Goal of the research

Retrieval of distribution of NO_2 in the troposphere over urban areas with better spatial resolution than currently operated satellite instruments



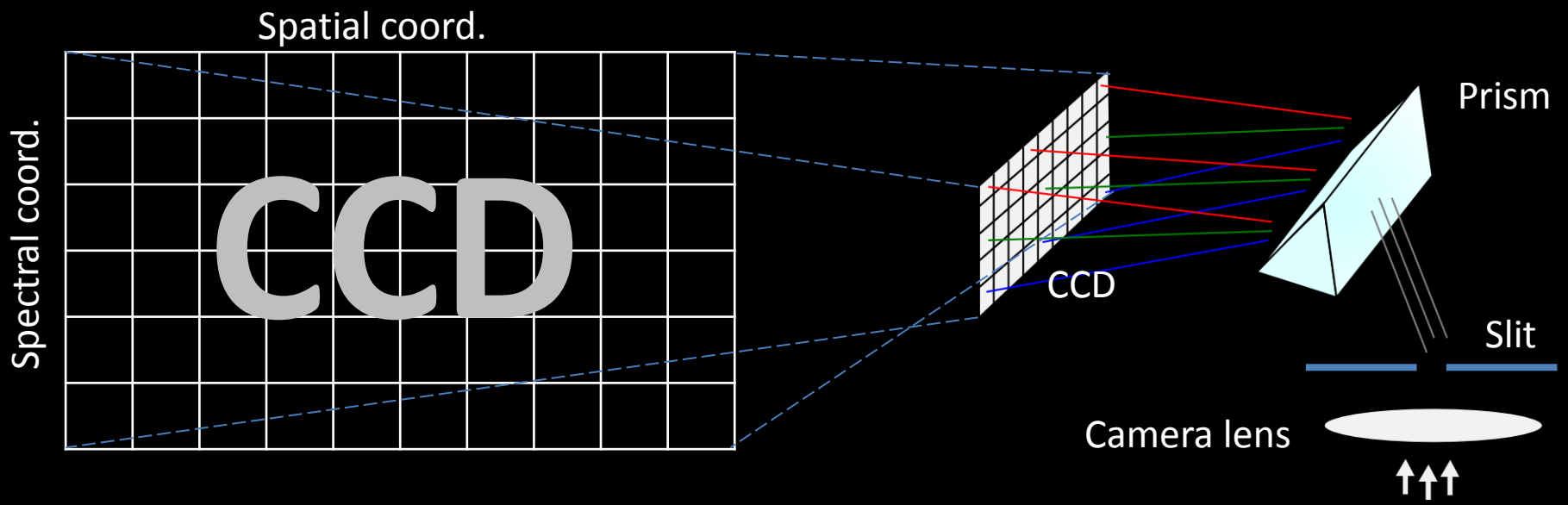
The satellite is designed for multi-spectral remote sensing of the Earth's surface aimed at acquiring high-quality visible images in near real-time as well as on-line data delivery via radio link and providing a wide range of consumers with value-added processed data.

Resurs-P is a series of Russian Earth-observing satellites capable of acquiring high-resolution imagery (max 30 m) in hyper-spectral mode

GSA instrument

Satellite	Launch date
Resurs-P №1	25.06.2013(not operate now)
Resurs-P №2	26.12.2014 (not operate now)
Resurs-P №3	13.03.2016 (not operate now)
Resurs-P №4	2023?
Resurs-P №5	

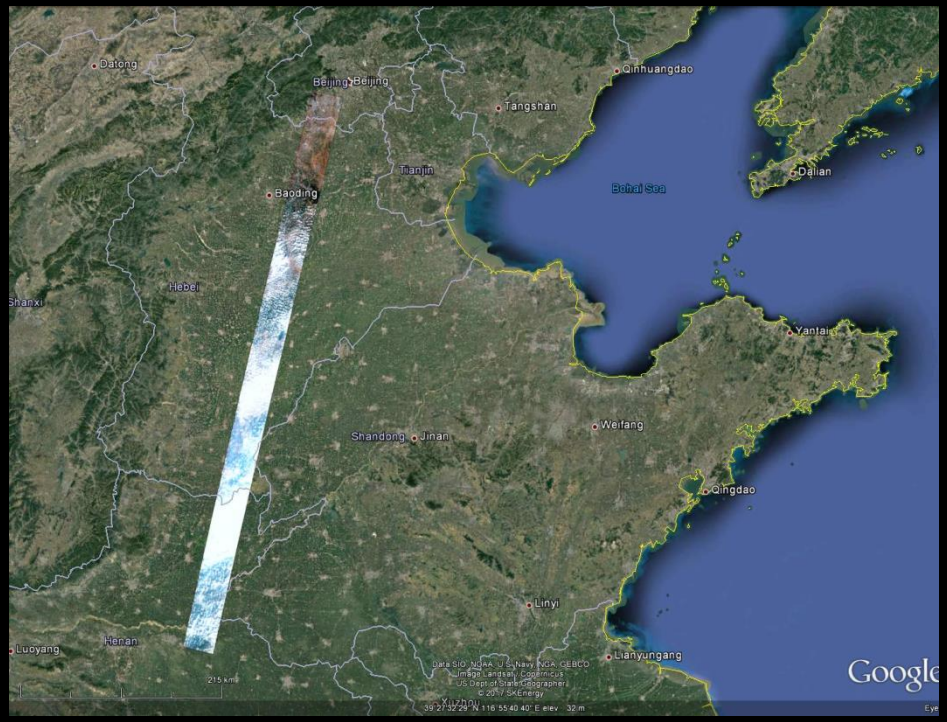
GSA/Resurs-P instrument characteristics



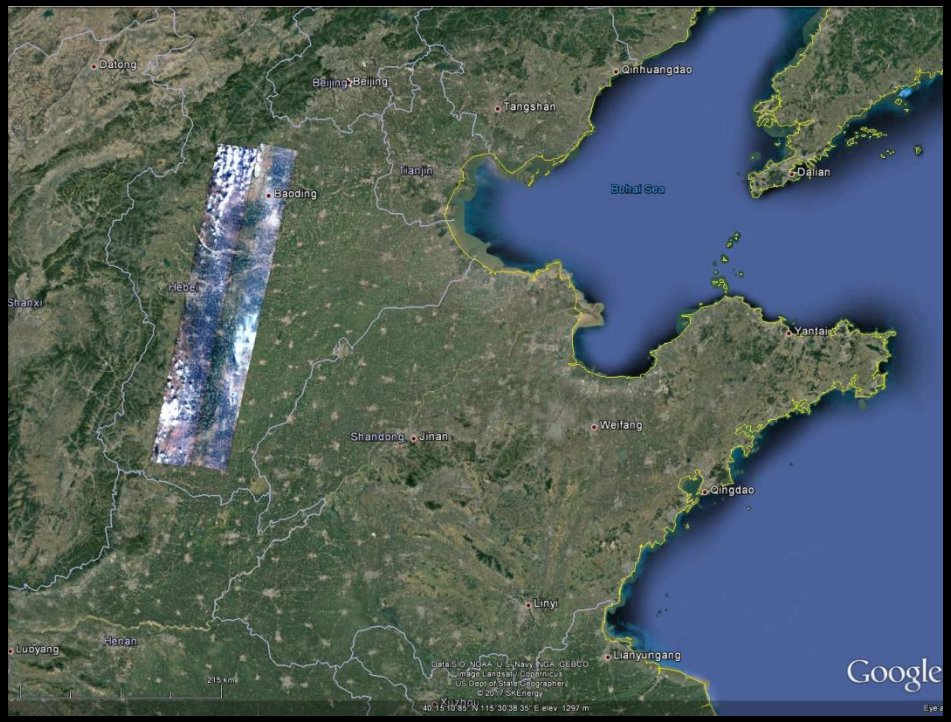
	NO_2 mode	Standard mode
Spectral resolution (FWHM)	3-4 nm (400-500nm)	up to 10 nm (400-1000 nm)
Frame size	30 (60-120) km × 2000+ km	30 km × 2000 km
Frame freq., rel. units	4	1
Binning (spectral × spatial pixels)	1×4	1…4×1
Pixel size	120 m × 120m	30 m × 30 m

Other possible frame sizes

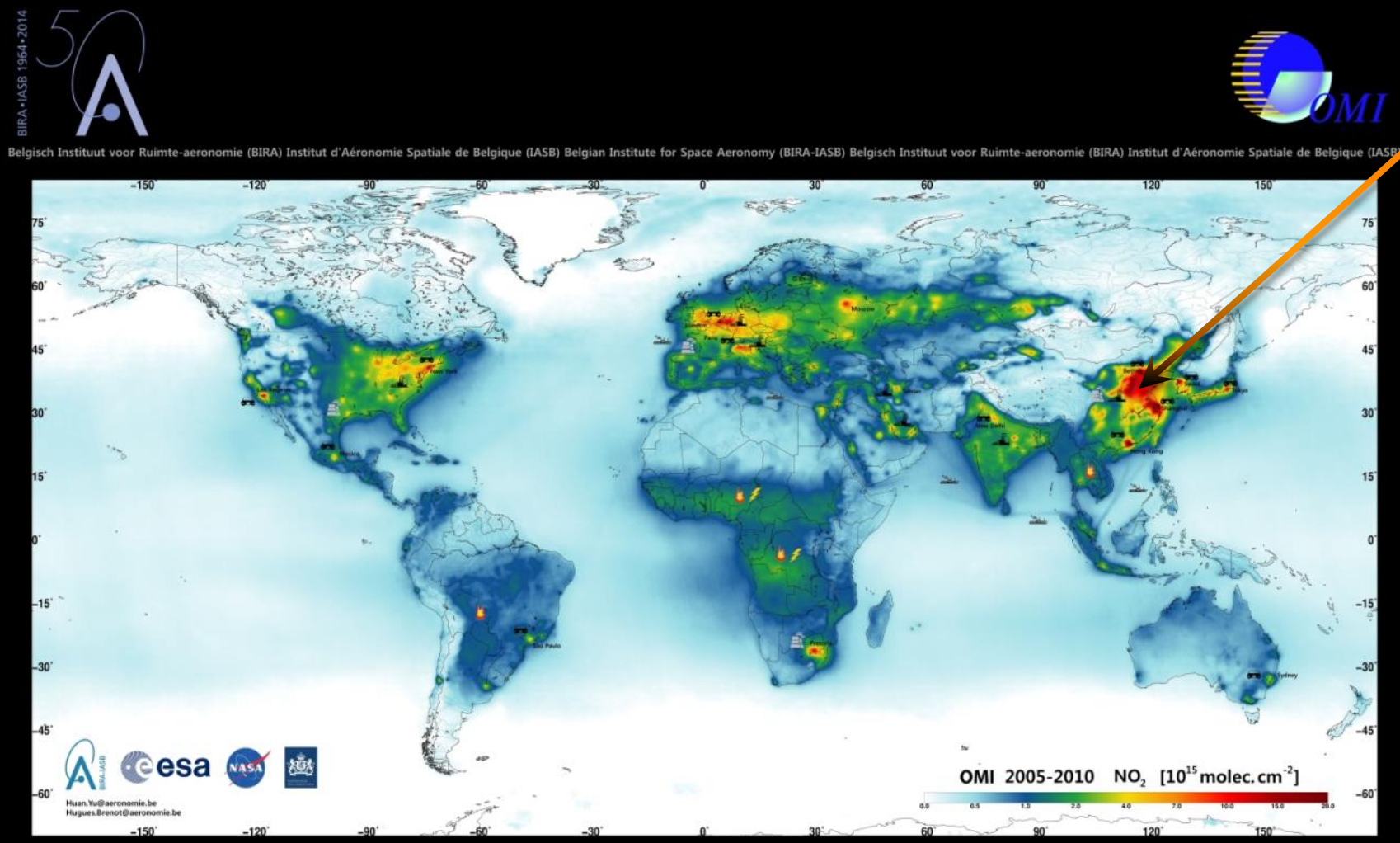
30 km x 600 km



60 km x 300 km



Location for the first experiment



Basics of method of NO_2 retrieval

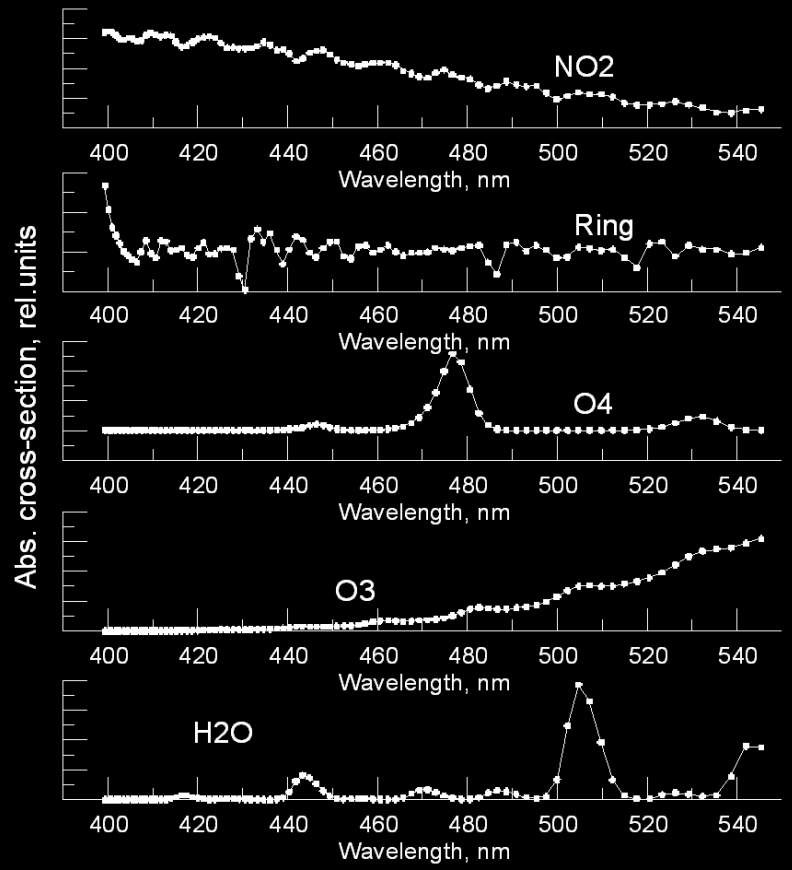
DOAS technique

$$I(\lambda_k) = I_0(\lambda_k) \cdot \exp\left(-\sum_i \sigma_i(\lambda_k) \cdot S_i\right)$$

$$S_i: \sum_k \left(ln\left(\frac{I_0(\lambda_k)}{I(\lambda_k)}\right) - \sum_i \sigma_i(\lambda_k) \cdot S_i\right)^2 \rightarrow min$$

$I(\lambda_k)$ - measured spectrum;
$I_0(\lambda_k)$ - reference spectrum;
$\sigma_i(\lambda_k)$ - absorption cross-section;
S_i - **slant column density (SCD)**.

DOAS – differential optical absorption spectroscopy

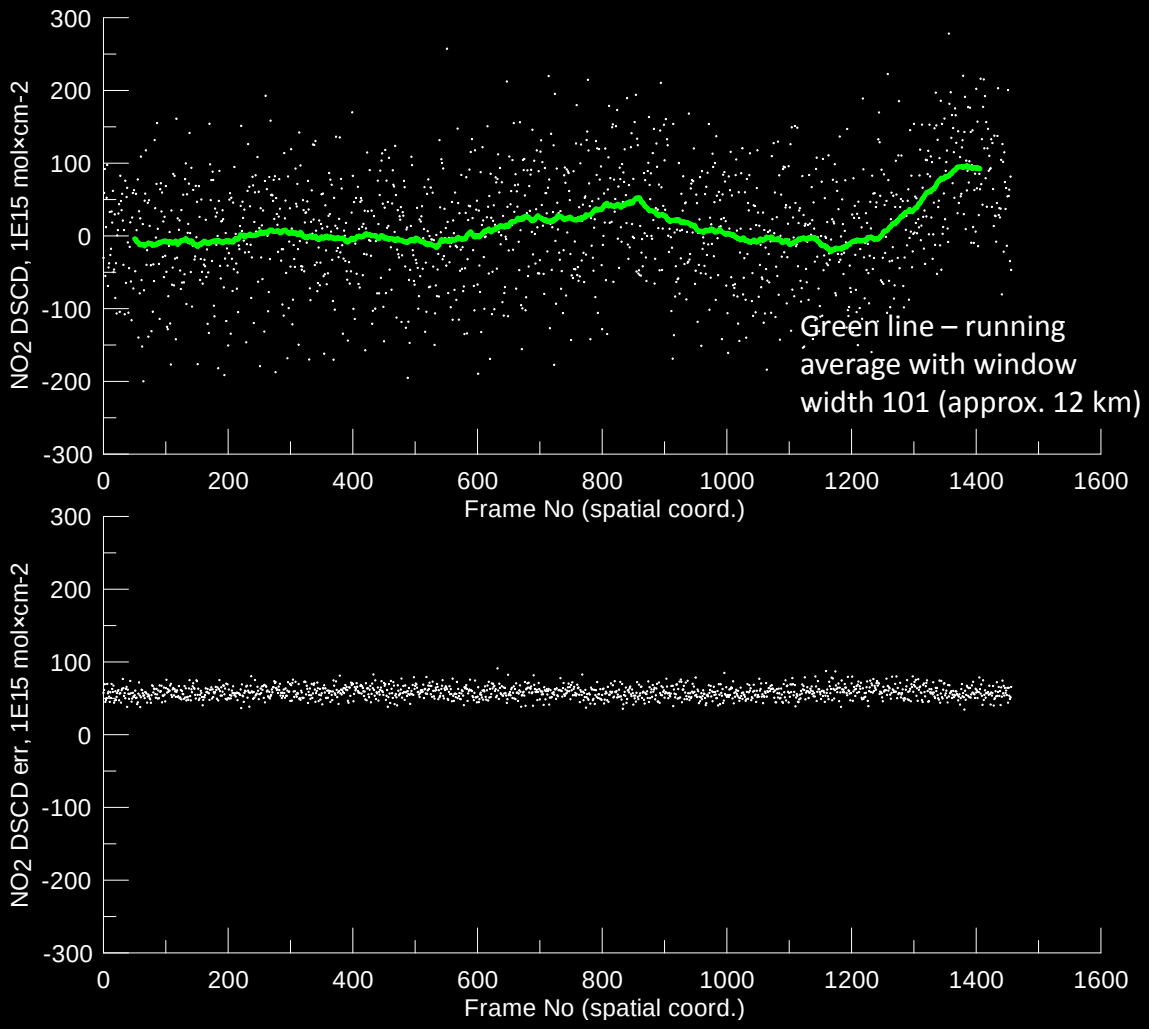


Cross sections convoluted with GSA instrument function.

$$\boldsymbol{V = S \cdot F} \qquad F = {1}\Big/{\int_{h_0}^{h_1} a(h)n(h)dh}$$

$\boldsymbol{a(h)}$ - weight coefficient of contribution for each atmospheric layer to the slant column (layer air mass factor (AMF)). It is calculated using a linearized RT model (for example MCC++).
V – vertical column density (VCD);
S – slant column density (SCD);
F – scaling factor

Retrieval errors of tropospheric NO_2 slant column



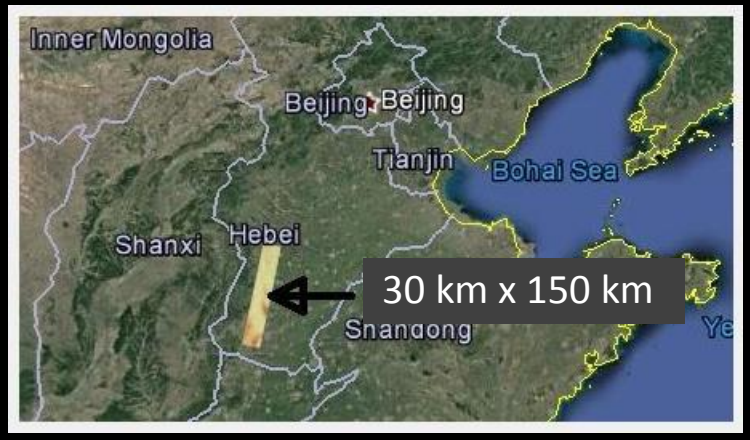
Error of single DSCD measurement (120x120m):
50*10^15 mol*cm^-2
Error for DSCD for averaged 400 pixels (2.4x2.4 km):
2.5*10^15 mol*cm^-2

Error for VCD for averaged 400 pixels (2.4x2.4 km):
(0.7-1.0)*10^15 mol*cm^-2
(for typical AMF=2.5-3.5)

Typical stratospheric VCD:
3…5*10^15 mol*cm^-2
Tropospheric VCD:
0…20…50…*10^15 mol*cm^-2

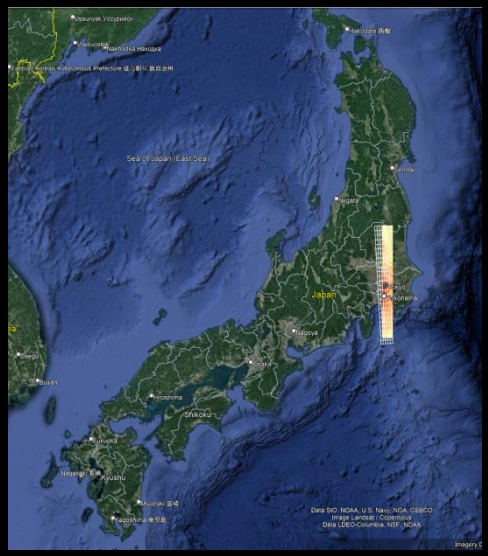
First NO2 maps with high spatial resolution

Observations of GSA/Resurs P №2
September 29, 2016, 4:30UTC

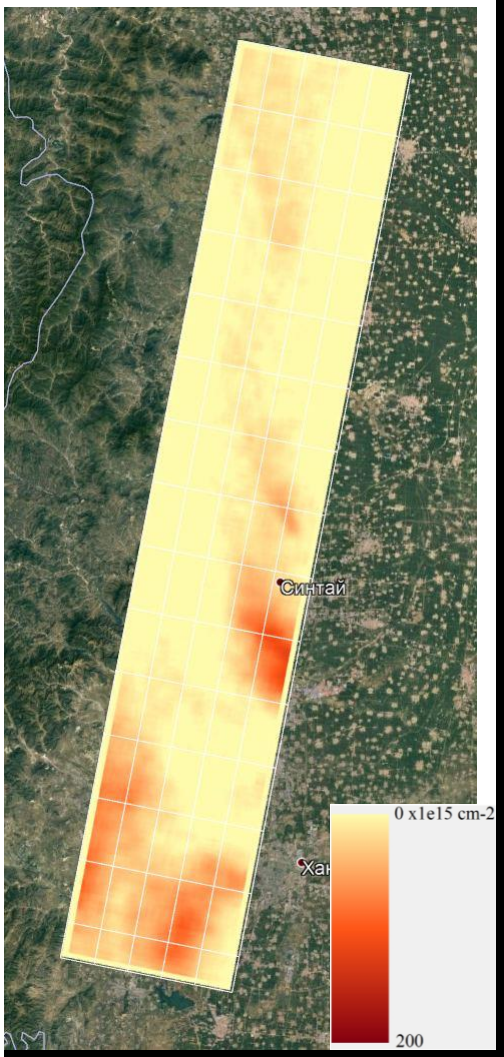


March 22, 2017

April 4, 2017



Resurs P №2:
Resolution 2.4 km,
grid step 120 m,
Slant column



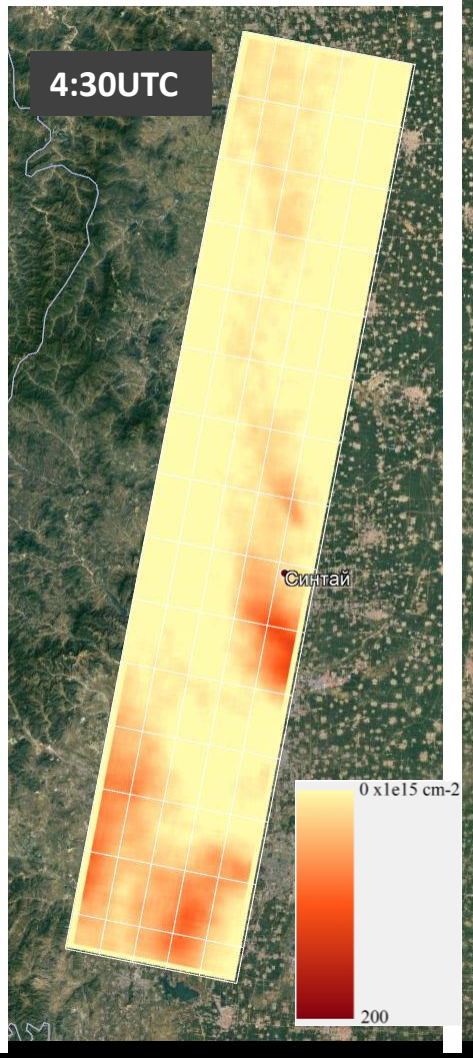
First NO2 map with high spatial resolution

Observations of GSA/Resurs P №2 taken on September 29, 2016, 4:30UTC

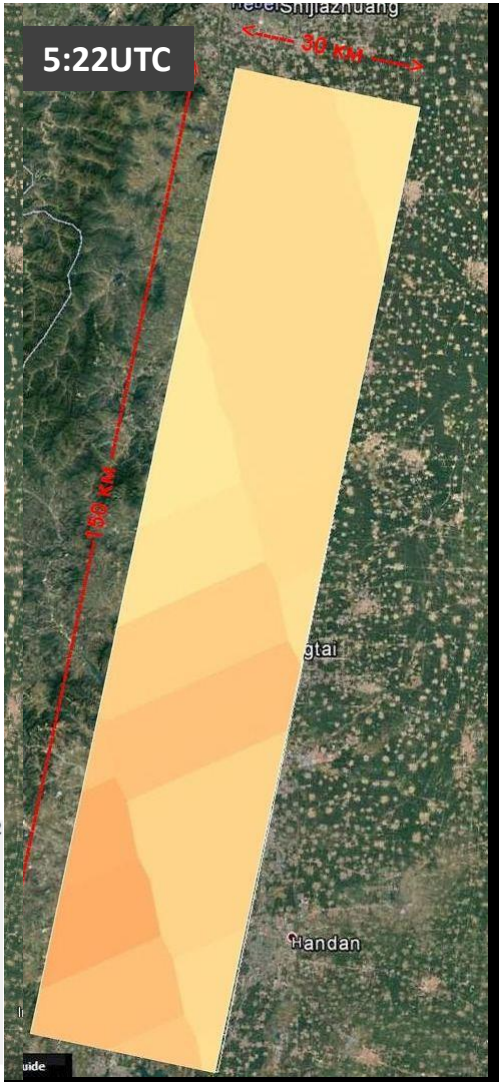
Validation of GSA/Resurs-P:

- Comparison with low-resolution data of other satellite (alternative high-resolution data don't exist).
- Comparison with high-resolution data of chemical-transport models.

Resurs P №2: plumes and sources are identified
Resolution 2.4 km, grid step 120 m



OMI: NO2 plumes and their source are hidden
Resolution 13kmx24km

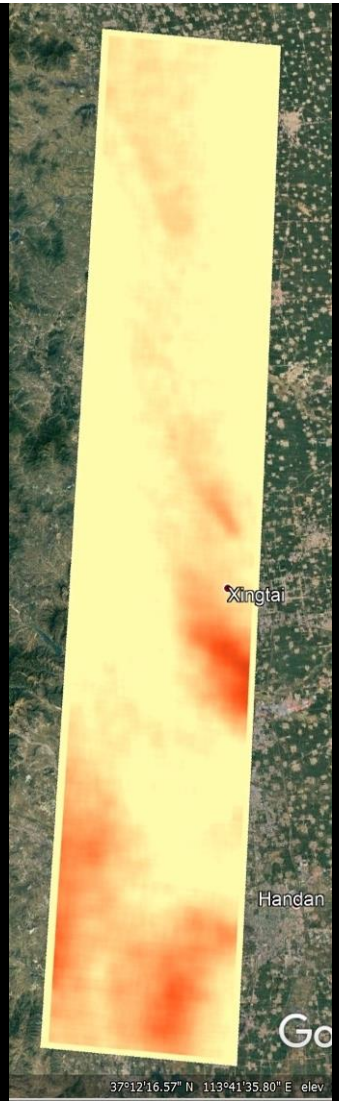


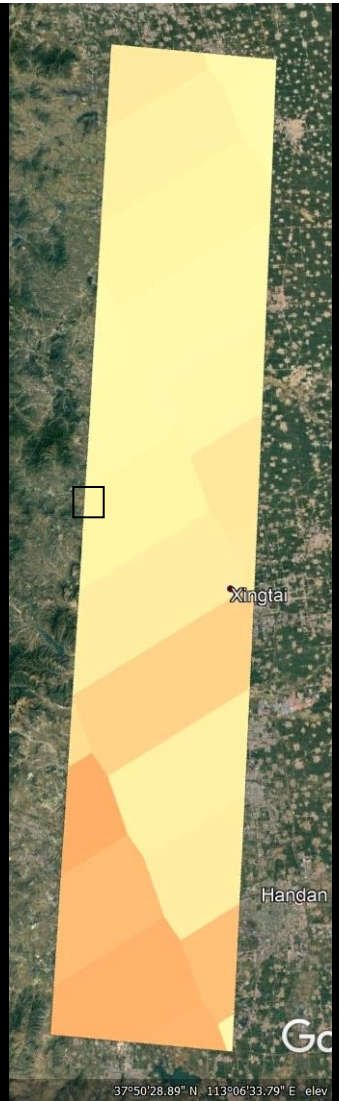
Comparison of NO2 DSCD data obtained by GSA and OMI

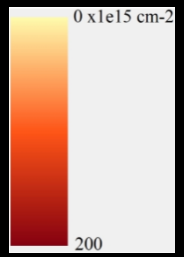
GSA/Resurs P №2, DSCD:
Resolution 2.4 km, grid step 120 m

Transformed to OMI grid

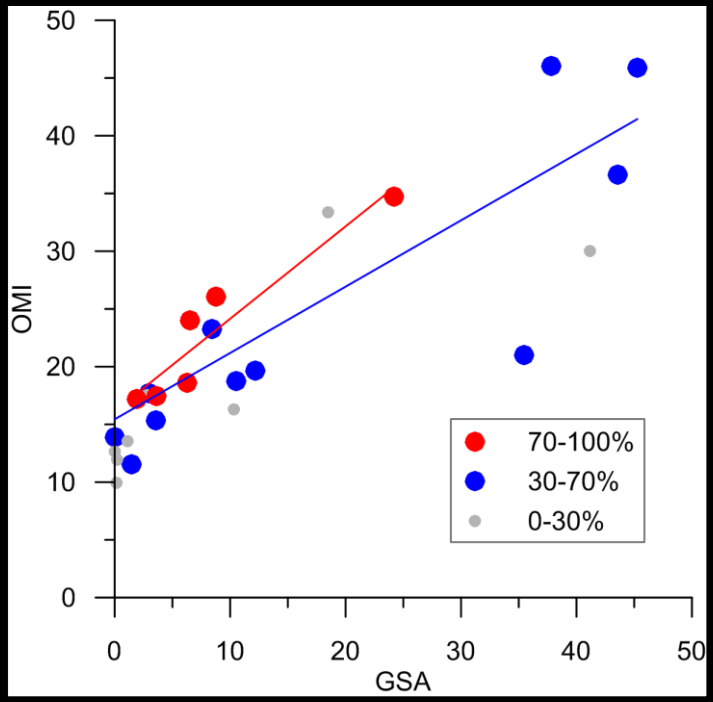
OMI (original grid), DSCD:
Resolution 13kmx24km







Comparison of NO2 DSCD data obtained by GSA and OMI



Fit Results

high+middle Fit
Equation Y = 0.5743238799 * X + 15.44307588
Number of data points used = 17
Average X = 14.8577
Average Y = 23.9762
Residual sum of squares = 470.723
Regression sum of squares = 1318.73
Coef of determination, R-squared = 0.736946
Residual mean square, sigma-hat-sq'd = 31.3816

Fit Results

highFit
Equation Y = 0.8001855961 * X + 16.14828444
Number of data points used = 6
Average X = 8.55239
Average Y = 22.9918
Residual sum of squares = 25.2808
Regression sum of squares = 205.839
Coef of determination, R-squared = 0.890616
Residual mean square, sigma-hat-sq'd = 6.32019

Comparison of NO2 DSCD data obtained by GSA and OMI (in 10^{16} molec×cm^{-2}). Color of circle corresponds to the percentage of the coverage OMI pixel by GSA data. Red regression line corresponds to coverage of more than 70%, blue one – more than 30%.

First NO2 map with high spatial resolution

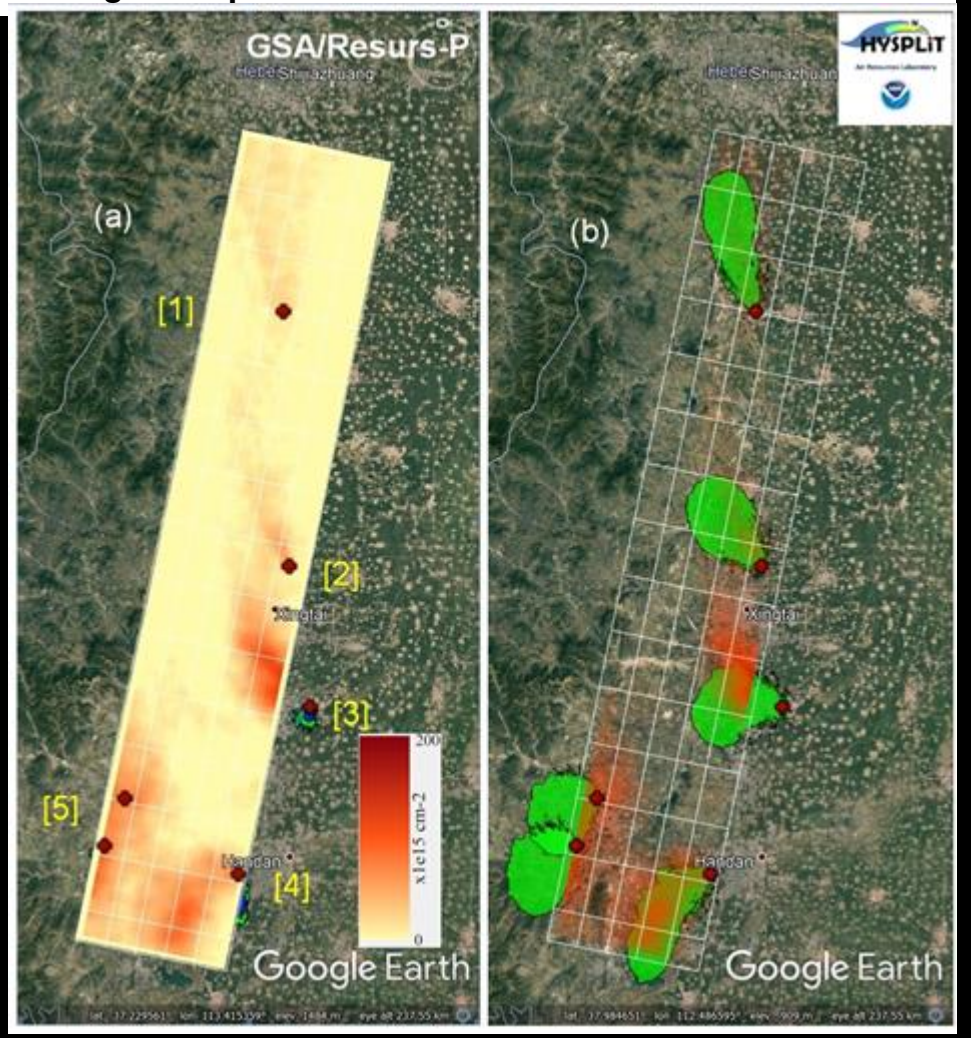
Observations of GSA/Resurs P №2 taken on September 29, 2016, 4:30UTC

Validation of GSA/Resurs-P:

- Comparison with low-resolution data of other satellite (alternative high-resolution data don't exist).
- Comparison with high-resolution data of chemical-transport models.

Resurs P №2: plumes and sources are identified Resolution 2.4 km, grid step 120 m

HYSPLIT dispersion model



NO2 source #2 in GSA NO2 map

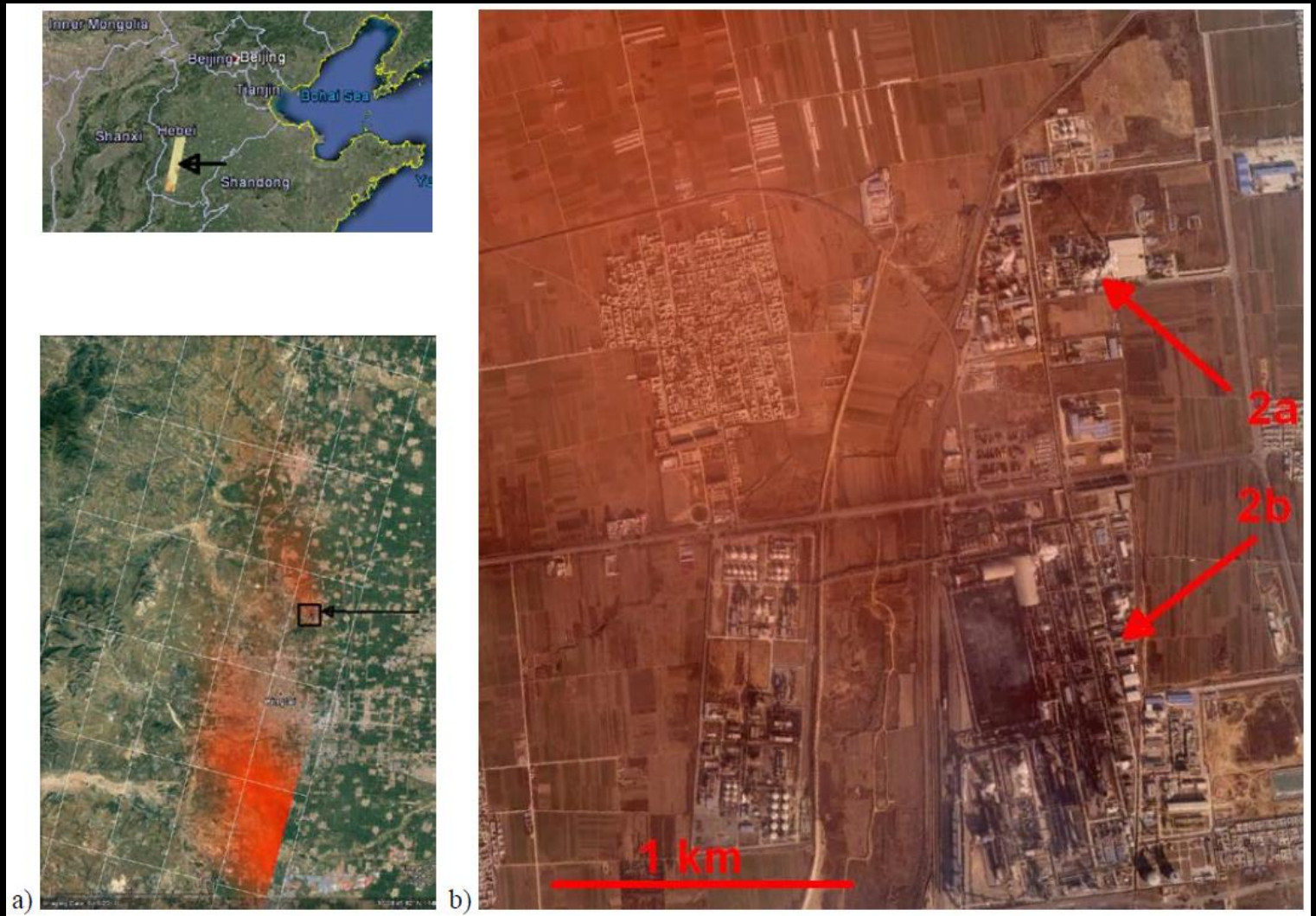
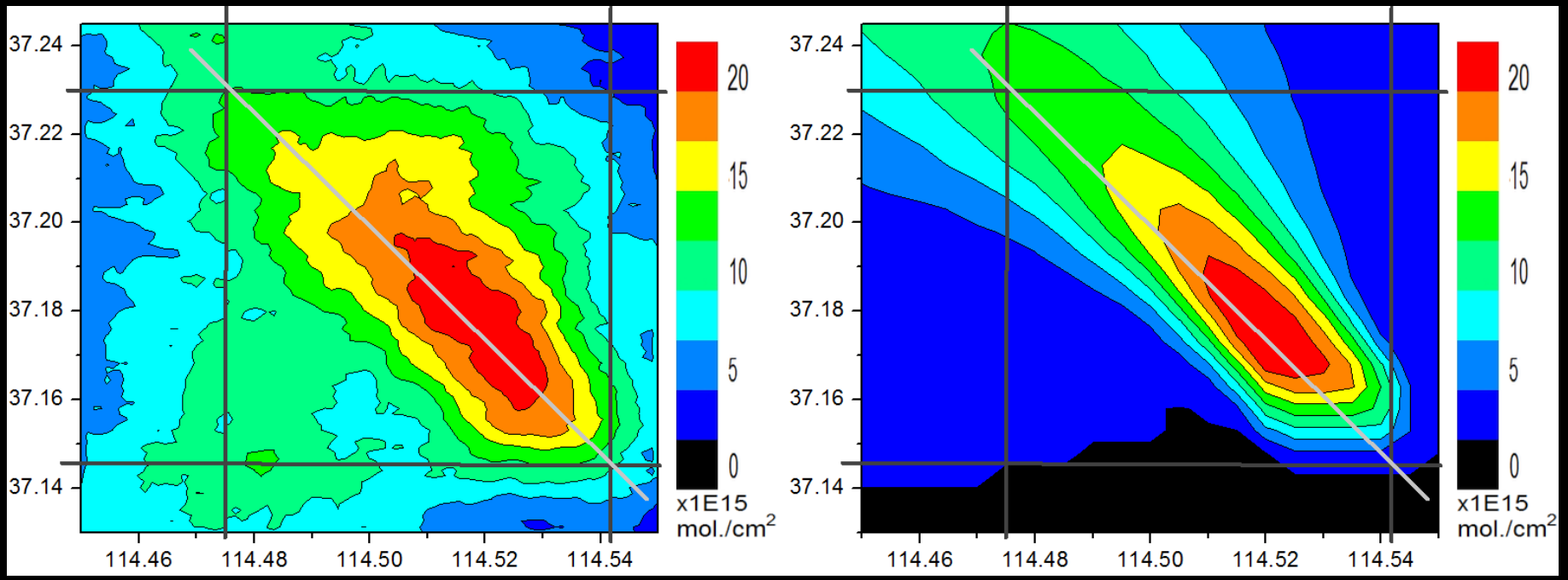


Figure 1. a) NO2 DSCD at 4:30UTC on September 29, 2016 retrieved by GSA algorithm. An arrow shows a square of a highly probable location of a source of NO2 pollution. b) The square from a) on an enlarged scale - some chemical industrial enterprise using coal, a possible source of the detected NO2 pollution. Maps of Google Earth for 12/2016 are used.

Simulation of plume #2 with numerical chemical transport model



a) The observed by GSA/Resurs-P plume #2, VCD obtained for geometrical AMF=3;
b) The result of the transport simulation of the plume #. Run using HYSPLIT Downloadable Public Version with quarter-degree meteorological data archive of NCEP Global Forecast System (GFS)

Simulation of plume #2 with numerical-asymptotic chemical transport model

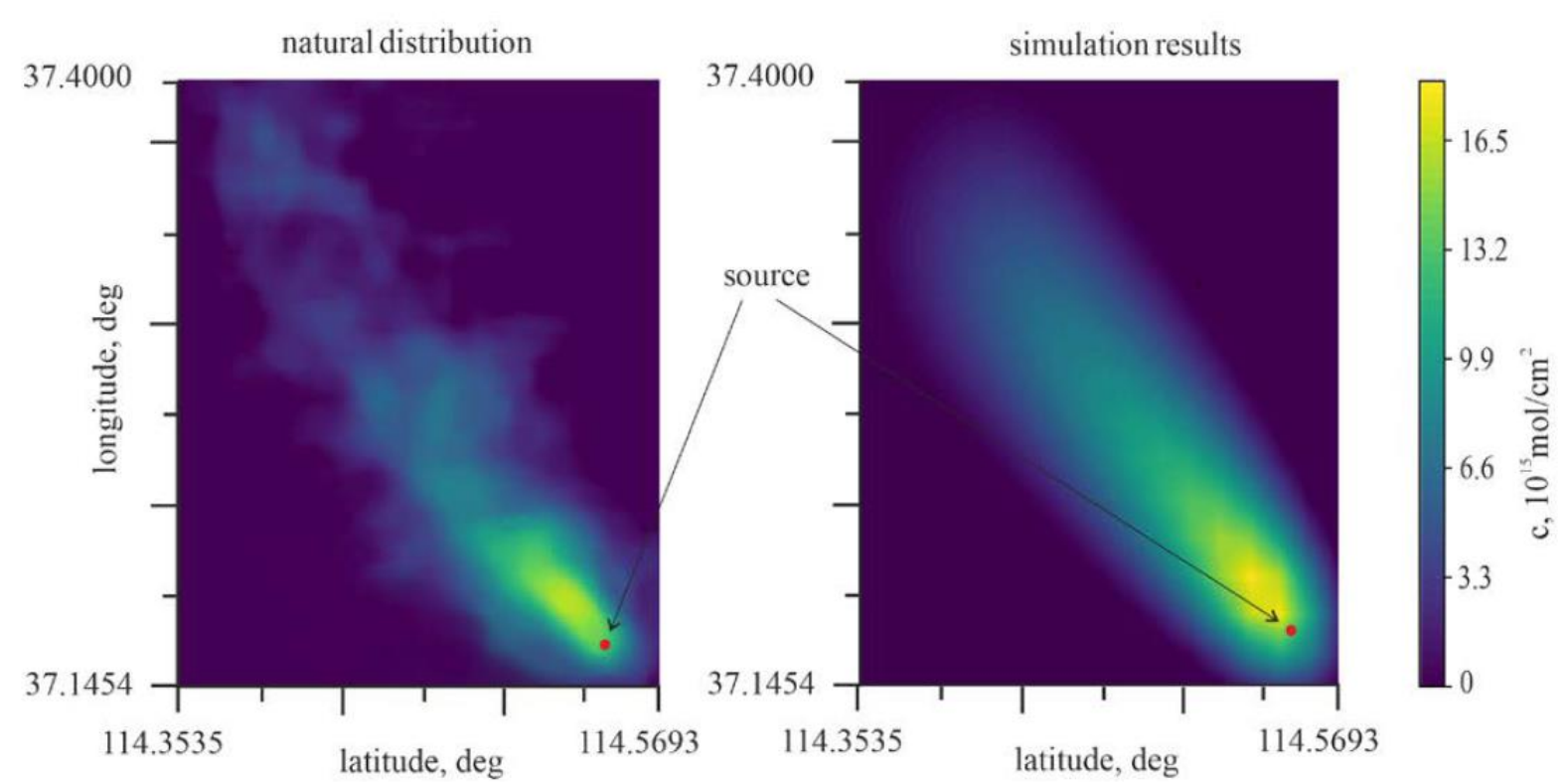


Figure 2. Measured (left) and simulated NO2 VCD (right) (Hebei Province, PRC September 29, 2016)

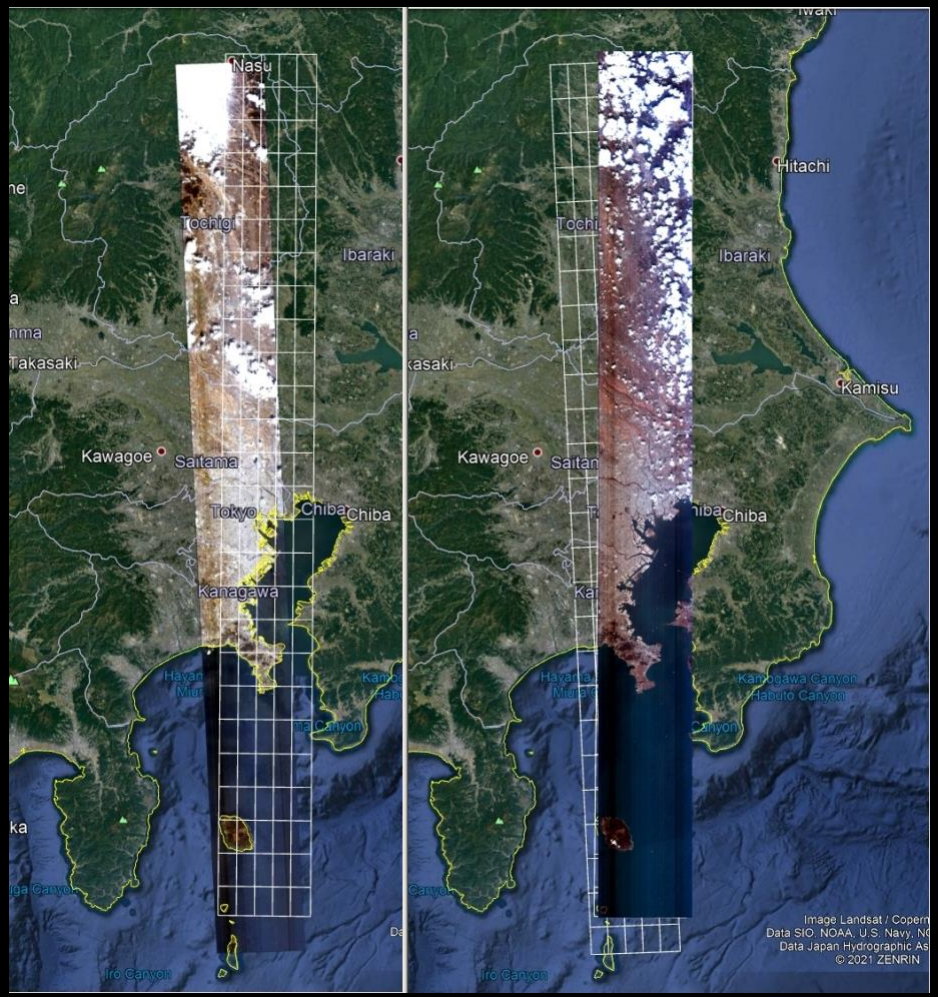
Based on the numerical-asymptotic approach, which take into account NO2 content in "the near-field zone" the estimate of NO2 emissions is about 100 kg/h

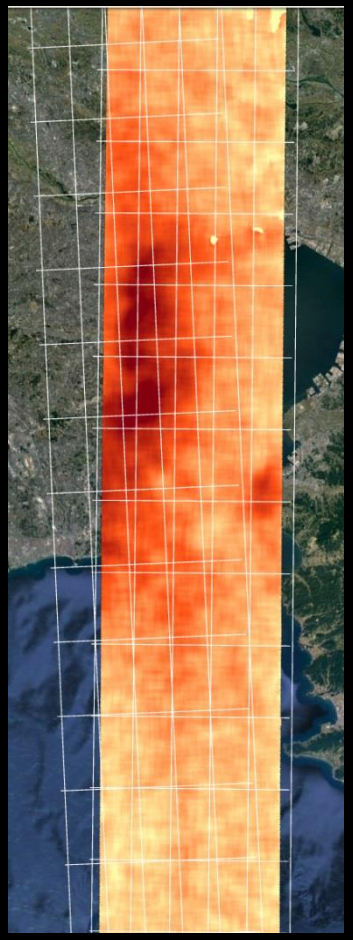
NO2 VCD obtained by GSA over Tokyo

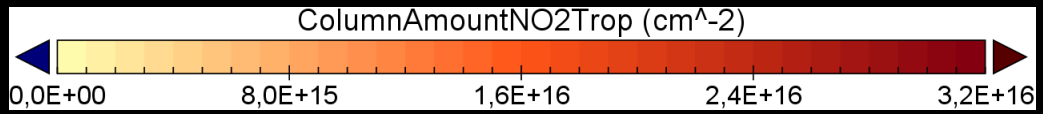
GSA/Resurs-P №2 :

22.03.2017

04.04.2017







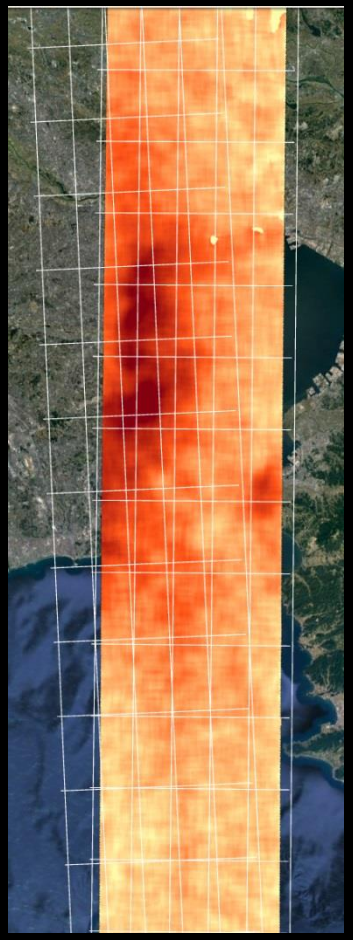
NO2 VCD obtained by GSA over Tokyo

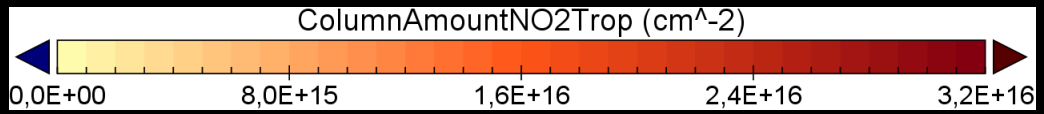
- March 22, 2017:
  Low NO2 content.
  The highest NO2 content is observed east of Tokyo over the bay.

- April 4, 2017:
  Significant NO2 content.
  The highest NO2 content is observed over Tokyo.

22.03.2017

04.04.2017





NO2 VCD obtained by GSA over Tokyo

- March 22, 2017:

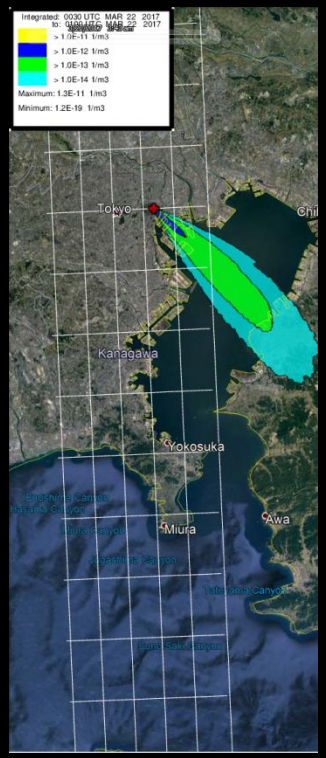
Low NO2 content. The highest NO2 content is observed east of Tokyo over the bay.

Northwest wind of 8 m/s was observed in Tokyo with gusts up to 15 m/s; this weather contributes to the dispersion of impurities.

- April 4, 2017:

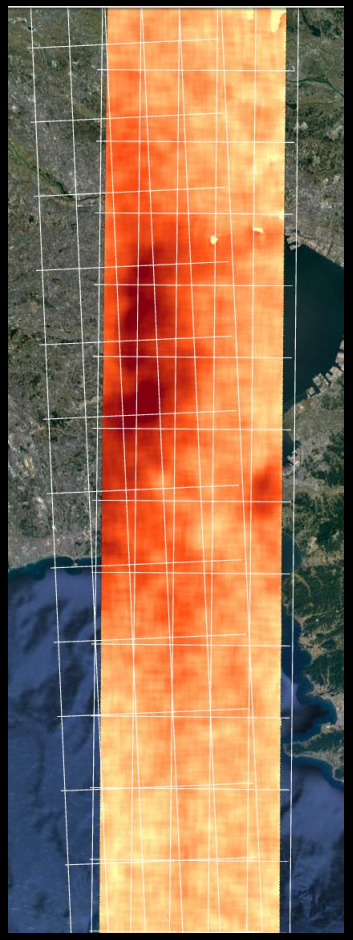
Significant NO2 content. The highest NO2 content is observed over Tokyo.

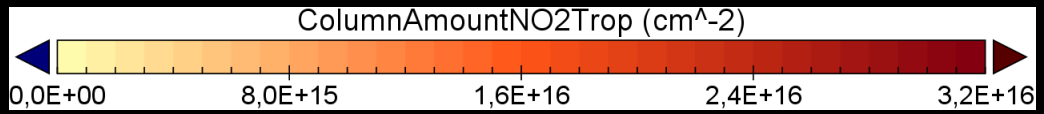
North-North-East wind of 1 m/s was observed; a quiet wind leads to a small dispersion of pollution.



22.03.2017

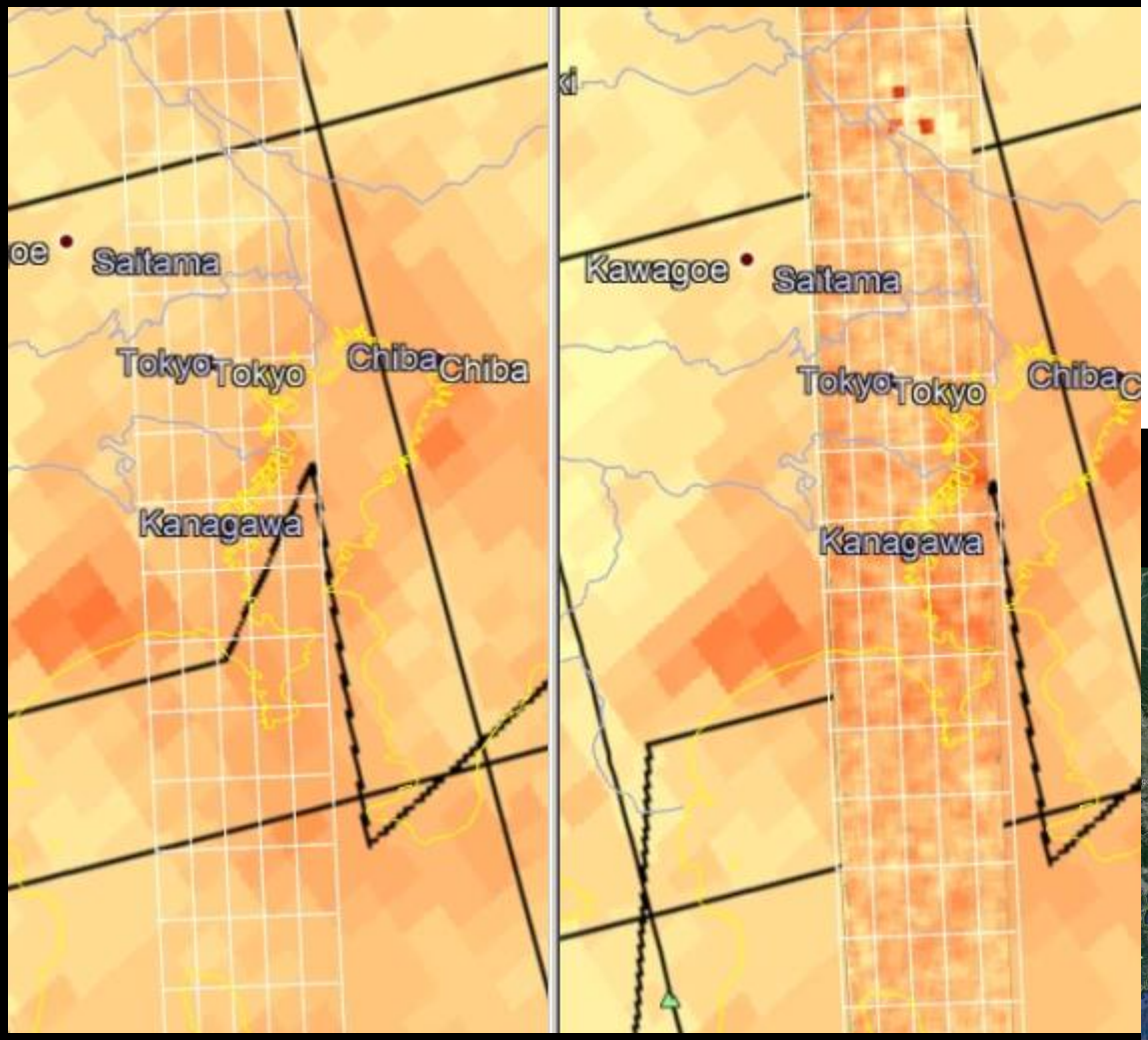
04.04.2017

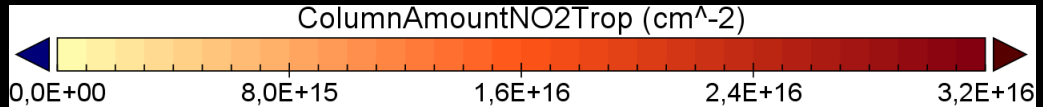




Comparison of NO2 VCD obtained by GSA and TROPOMI

TROPOMI/Aura 15.03.2021 GSA/Resurs-P №2 : 22.03.2017





TROPOMI data under similar meteorological conditions

- ❑ GSA: March 22, 2017, 2.4kmX2.4km

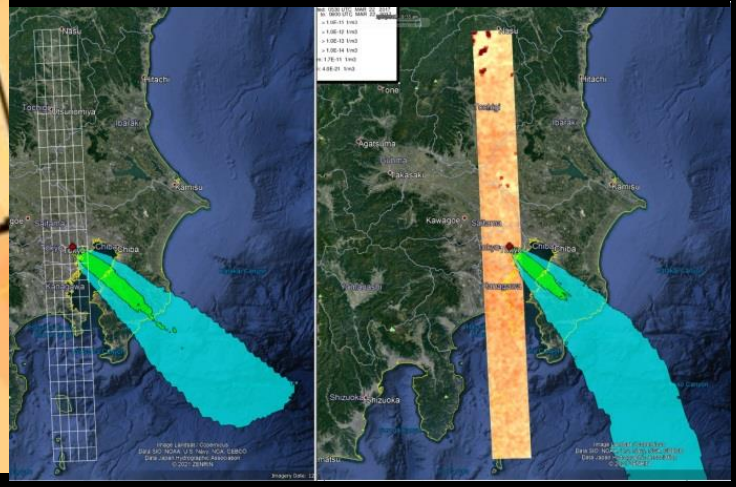
Low NO2 content.
The highest NO2 content is observed east of Tokyo over the bay.
Higher abundances are observed north of Yokosuka up to Yokogama.

- ❑ TROPOMI: March 15,2021,8.5kmX5.5km

Low NO2 content.
High NO2 content is observed east of Tokyo over the bay.
Higher abundance in south of Yokosuka.

15.03.2021 22.03.2017

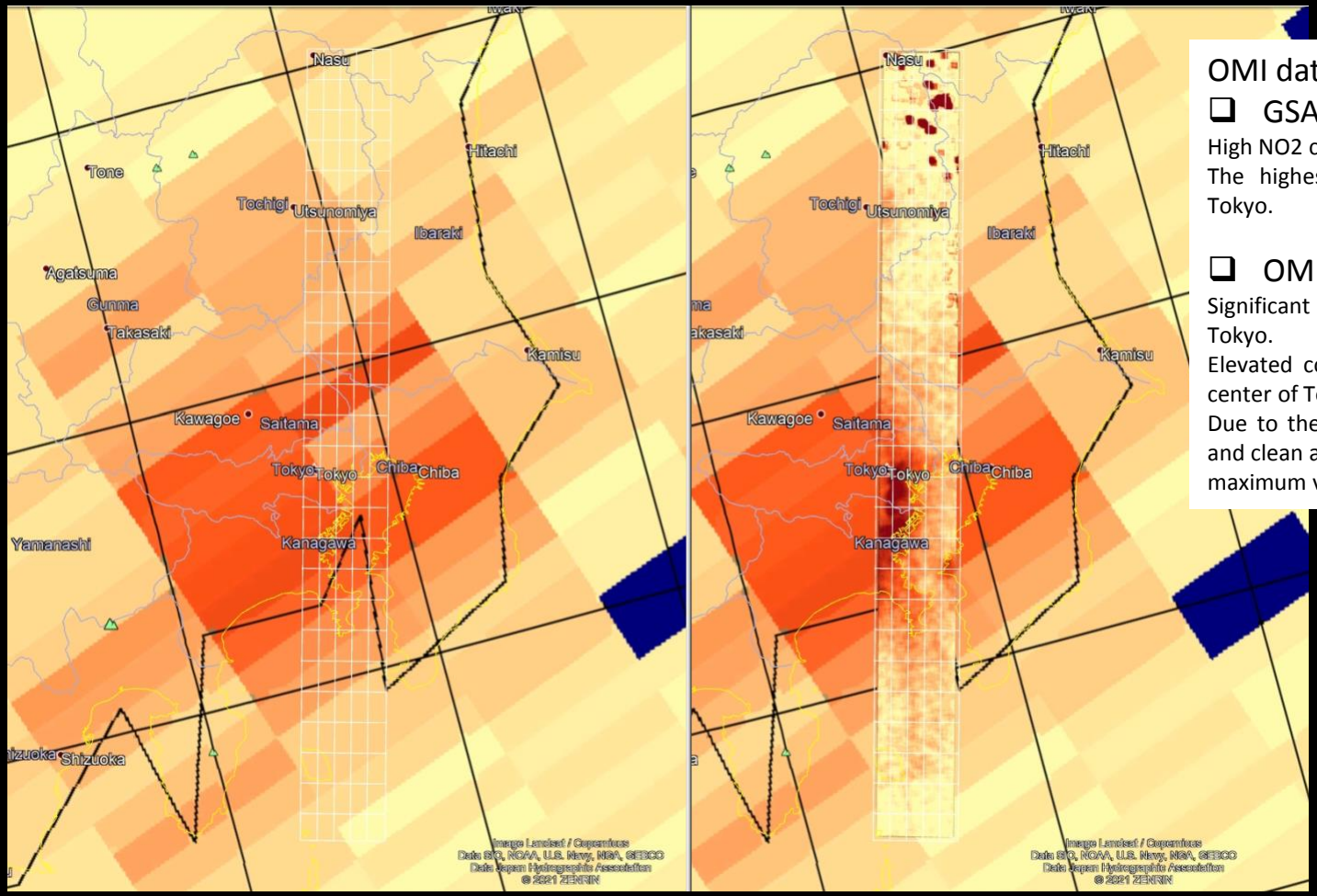
HYSPLIT dispersion model

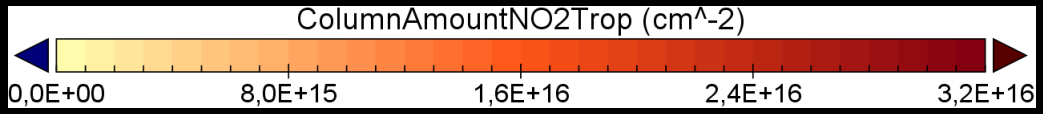


Comparison of NO2 VCD obtained by GSA and OMI

OMI/Aura 04.04.2017

GSA/Resurs-P №2 04.04.2017





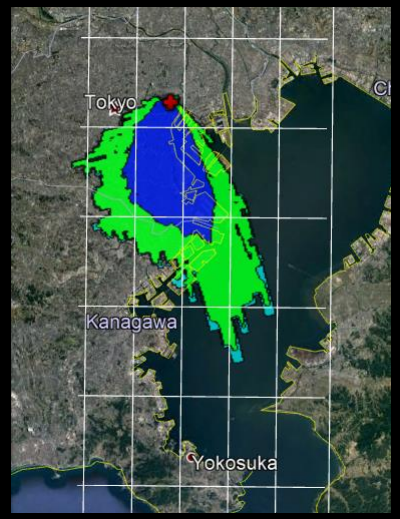
OMI data for the same day

- ❑ GSA: 2.4kmX2.4km

High NO2 content over Tokyo.
The highest NO2 content is observed over Tokyo.

- ❑ OMI: 13kmX60km

Significant NO2 content in pixels covering Tokyo.
Elevated content to south/south-west of the center of Tokyo.
Due to the fact that larger pixels cover urban and clean areas, the instrument records a lower maximum value.



Conclusion

- Пространственное разрешение измерений NO2 ГСА/Ресурс-П №2 и №3 составляет около 2,4 км с шагом сетки 120 м и превышает разрешение других спутниковых приборов.
- В целом измерения тропосферного NO2 по GSA/Ресурс-П согласуются с измерениями OMI и TROPOMI, но превосходят их по разрешающей способности.
- Использование прибора ГСА/Ресурс-П позволяет исследовать тонкую структуру распределения NO2.
- Выполнены первые оценки мощности излучения локального источника по спутниковым измерениям (с привлечение химически-транспортных моделей соответствующего разрешения).
- Целесообразно использовать приборы Ресурс-П №4 и №5 в сочетании с TROPOMI или OMI для улучшения разрешения получаемого поля NO2 в выбранных местах.

СПАСИБО ЗА ВНИМАНИЕ!

THE WORK WAS SUPPORTED BY RUSSIAN FOUNDATION FOR BASIC RESEARCHES
WITH GRANTS 20-05-00826