Application of fuzzy filtering for thermal infrared satellite data resolution enhancement

Elena Zaitseva, Mykola Lubskyi, Ján Rabčan

Abstract — proposed technique for satellite thermal infrared imagery spatial resolution enhancement involves frequency domain imagery processing using Fast Fourier Transform. This paper consider approach of frequency components separation, that are appropriate for existing spatial resolution enhancement technique, which require the pair of images of the same area with subpixel shift. This method allow enhance detalization and informativity of existing long-term data of Landsat legacy satellite data, that exists since 1984 and will be useful for data received by future satellites, like Landsat-9.

Keywords — fast Fourier transform, frequency domain processing, fuzzy filtering, longwave infrared imagery, remote sensing satellite data, resolution enhancement.

I. INTRODUCTION

The Landsat program, as the product of collaboration between United States Geological Survey (USGS) and National Aeronautics and Space Administration (NASA) has provided accurate measurements of Earth's land cover since 1972. Since 1984, with launch of Landsat-4 satellite, this program started providing longwave infrared data in the wavelength range 10.3-12.5 µm that corresponds to low-energy heat radiance. Along all this period Landsat satellites remains the only satellite program, which promptly provides longwave infrared imagery with moderate spatial resolution (< 100 m). This data help to resolve many tasks, which consider land or subterranean heat radiance: volcanoes activity [1], sea surface temperature changes [2], definition of surface CO_2 expiration [3], urban heat island research [4], etc. Due to rapid urbanization process problem of urbanized area heat emission became extremely especially important. In addition, urbanization with cities population increasing is also closely related to industrial areas expansion. All these factors leads to expansion of surfaces with capability of heat accumulation: asphalts, concrete, roofing rubber, metal roofs etc. which emits heat backwards to atmosphere during night period, keeping urbanized area's air overheated. This heat-transferring regime affects population health pernicious.

Longwave infrared data from Landsat satellites became the basis for surface temperature mapping. Many researches of the urbanized area heat islands using Landsat-8 data are already conducted [5, 6]. Landsat data also provides the possibility of long-term time series processing for regression analysis and microclimate condition prediction [7]. However, relatively low spatial resolution of raw Landsat longwave infrared data remains the problem, which do not allow detailed mapping of territories with high landscape and surface heterogeneous, like cities.

Different approaches for resulting temperature images spatial resolution enhancement technique are exist. Fast Fourier Transform (FFT) allows expanding of imagery processing possibilities. It transforms images from spatial domain into frequency domain and represent it like set of frequency components. It permits frequency filtration for many purposes: noise attenuation [8], windowed filtration [9], etc. FFT proved to be very flexible and efficient technique, and it is allow separate frequency component separation for purposes of spatial resolution enhancement.

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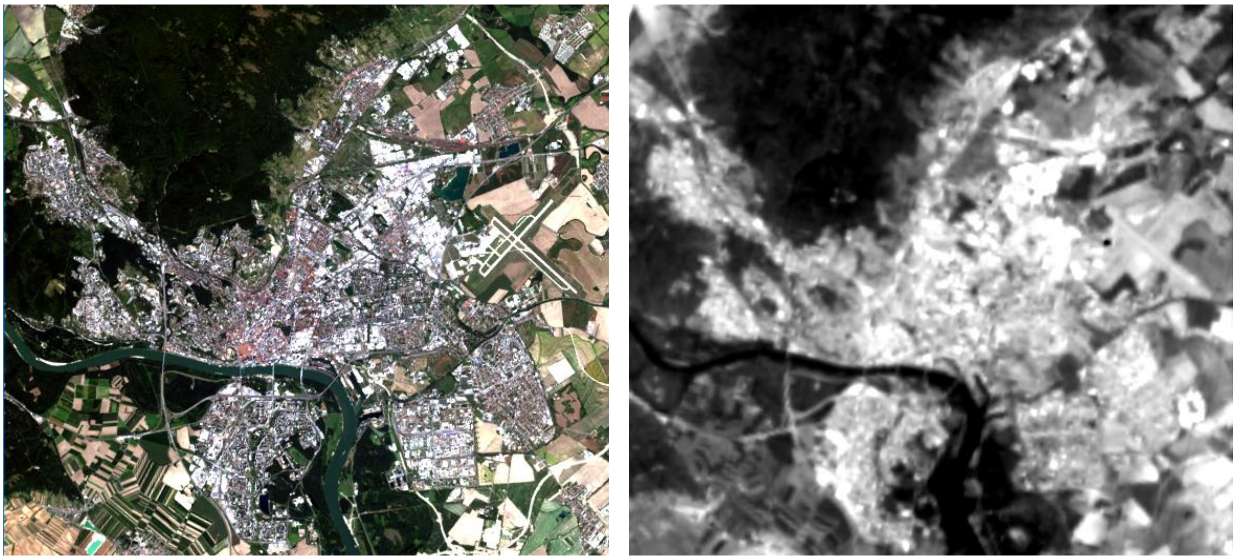
II. Dataset and Methods

A. Landsat data receiving

Landsat data also as many other types of remote sensing data are provided by USGS web-service EarthExplorer (https://earthexplorer.usgs.gov/). All presented data is in free access. The EarthExplorer user interface is an online search, discovery, and ordering tool, with powerful filtering tools and area search interface, based on GoogleMaps. Landsat archive contains images in all spectral bands, including longwave infrared data, in GeoTIFF format.

For this research a pair of Landsat-8 imagery stack were acquired. Study area – capital of Slovakia Bratislava. Dates of imagery acquisition 12 August, 2018 and 28 August, 2018. As the typical city Bratislava contain a lot of different landscapes and surfaces: parks, roads, metal and rubber roofs with physical dimensions much more lover than spatial resolution not only TIRS sensor but also OLI. This makes superresolution task especially important for urbanized area imagery, that contains surface temperature. Fig. 1 demonstrates raw Landsat-8 data of the data from 12 August, 2018.



a *b*

Fig. 1 Landsat-8 imagery of Bratislava city (12 August, 2018): *a)* visible data, provided by OLI sensor (combination of the 2, 3 and 4 band), *b)* longwave infrared data provided by TIRS sensor (10 band)

B. Temperature and emissivity estimation

Temperature distribution image is the main result of the long-wavelength infrared data processing of the radiance data, which is derived with taking into account the influence of atmospheric effects. For precise determination of the land surface radiance it is necessary to eliminate the influence of the atmosphere caused by the presence of atmospheric trace gases, water vapor that absorb, reflect and scatter infrared radiation [10]:

$$L_\lambda = \varepsilon_\lambda \tau_\lambda \int L_{b\lambda} S_\lambda + L_\lambda^{\uparrow} + \left(1-\varepsilon_\lambda\right)\tau_\lambda L_\lambda^{\downarrow}, \qquad (1)$$

where L_λ – spectral radiance in spectral range λ; ε_λ – spectral emissivity in spectral range λ; τ_λ – spectral atmospheric transmittance; $L_{b\lambda}$ – spectral emittance of the blackbody; S_λ – sensor's normalized spectral response $c_1 = 2hc^2 = 1{,}191\cdot10^{-16}$ W·m^2 and $c_2 = 1{,}439\cdot10^{-2}$ m·K – first and second Planck's constant; λ – radiance wavelength; $L_\lambda^{\uparrow}$ and $L_\lambda^{\downarrow}$ – upwelling and downwelling irradiance.

Planck's law is the equation for temperature determination:

$$T = \frac{c_2}{\lambda \ln\left(\frac{\varepsilon_\lambda c_1}{\lambda^5 L_s} + 1\right)} \tag{2}$$

where Ls – spectral radiance from the Earth's surface; c_1 = 2hc^2 = 1,191·10-16 W·m2 and c_2 = 1,439·10^{-2} m·K – first and second Planck's constant.

The emissivity can be estimated on the basis of the visible and near infrared (NIR) data processing. Determination of the Earth's surfaces emissivity distribution using remote sensing data is performed by processing images of the visible and near-infrared range, in particular by establishing of the relationship between emissivity the normalized difference vegetation index (NDVI) distribution [11]. The emissivity is a rather inert surface feature, and for its determination it is possible to involve data obtained with some time interval in comparison with the data of the long-wavelength range. The determination emissivity and the NDVI index relationship for the surfaces covered with vegetation and bare soil is established separately from other types of surfaces, including artificial ones.

This relationship for nonvegetation covers is estimated on the basis of the regressive dependence between artificial surfaces spectra taken from ASTER Spectral Library (http://speclib.jpl.nasa.gov) and NDVI index beyond its range that corresponds to the vegetation cover. Derived quasi-optimal spline-approximation of the dependence is performed through the obtained averaged point (Fig. 2).

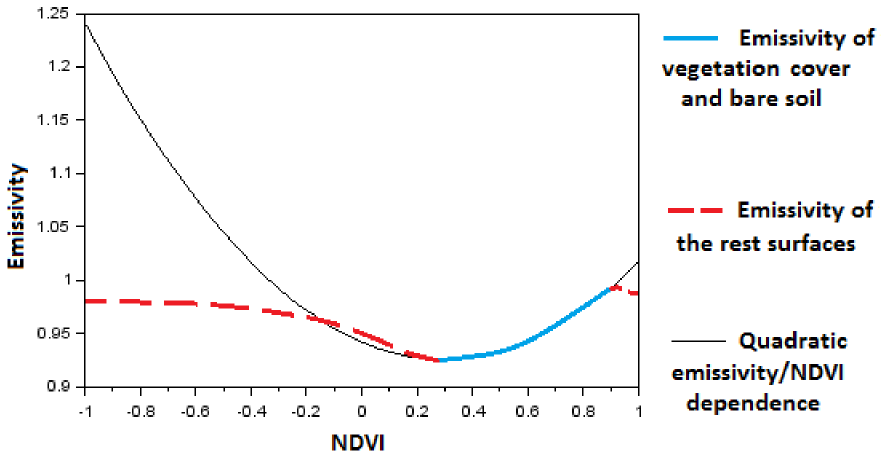


Fig. 2 Distribution of the relationship between Earth's surfaces emissivity and NDVI vegetation index

This approach of emissivity estimation allows obtaining sufficiently detailed data on the thermal characteristics of the presented landscapes and significantly improving the informativity of the resulting surface temperature distribution relatively to the raw Landsat longwave infrared data (Fig. 3).

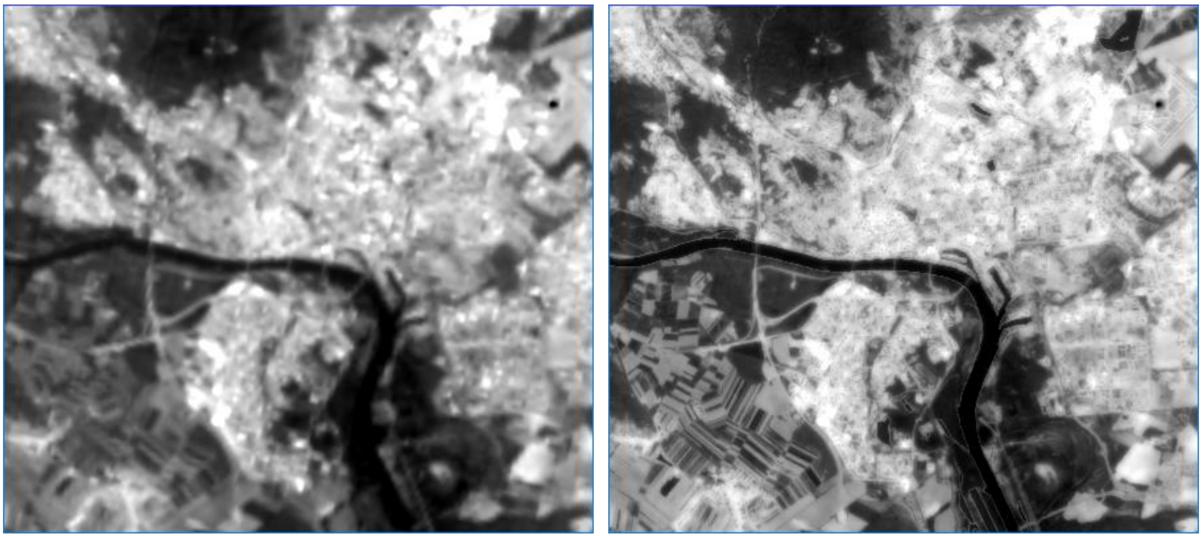


Fig. 3 Visual comparison between detalization of raw longwave data from Landsat-8 (left) and processed surface temperature image (right)

Detailed temperature end emissivity estimation procedure presented in [12].

C. Basics of subpixel spatial resolution enhancement technique

Subpixel superreosution technique [13] is based on specific processing of minimum two images of the same territory with subpixel shift, with distribution of the same feature and radiometrically equivalent. Subpixel offsets are stochastic linear deviations of pixel nets per pixel share that occur when rescannig the same area. In case of using temperature data, those images must be taken in the same time, otherwise temperature difference would make distortions in resulting enhanced image. This technique extracts features from both of images, what makes spatial resolution enhancement possible.

Obtaining an image of enhanced spatial resolution from a pair of images of low spatial resolution is achieved by realization of the next actions:

- subpixel shift estimation;
- estimation of the joint noise image as the difference between input images;
- merging of low-resolution input images into a common resampled image by interlaced scan into a grid of high resolution with replacing two pixels diagonally with pixels of input images, taking into account the subpixel offset and noise matrix;
- estimation of the inverse operator matrix estimation, for the rest of the pixels restoration;
- enhanced image restoration;
- iterative image reconstruction for irregularities and suppress noise elimination.

The corresponding software has been developed to perform the procedure for restoring the high definition image [13].

Emissivity for a period of Landsat revisit time (up to 16 days) used to be an appropriate data for sub-pixel processing. However, the proposed improvement for this technique allow adopting it for temperature images processing, despite the significant temperature difference. Frequency domain processing permit extracting particular frequency components, which can be utilized instead of emissivity images.

D. Fuzzy imagery filtering in frequency domain

FFT allows transferring data from spatial or time domain into frequency domain. Amplitude spectrum as the main output data for gives detailed information about frequency components, contained in image and its’ direction across the image (Fig. 4).

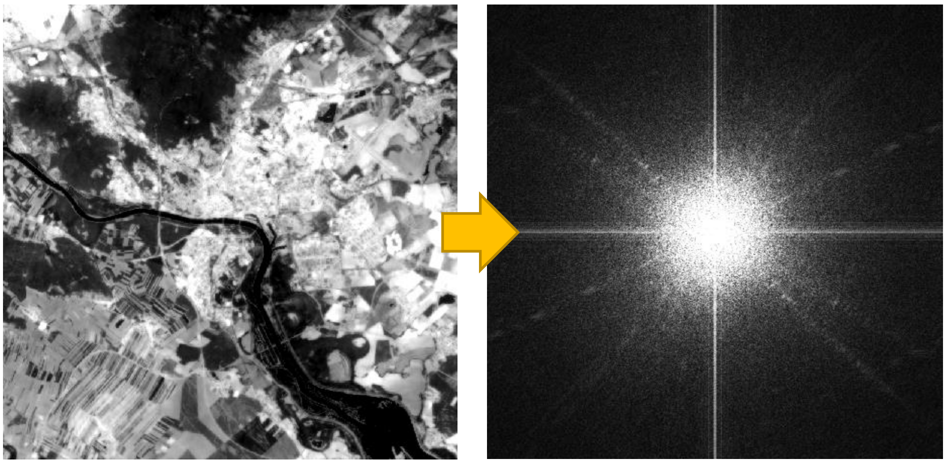
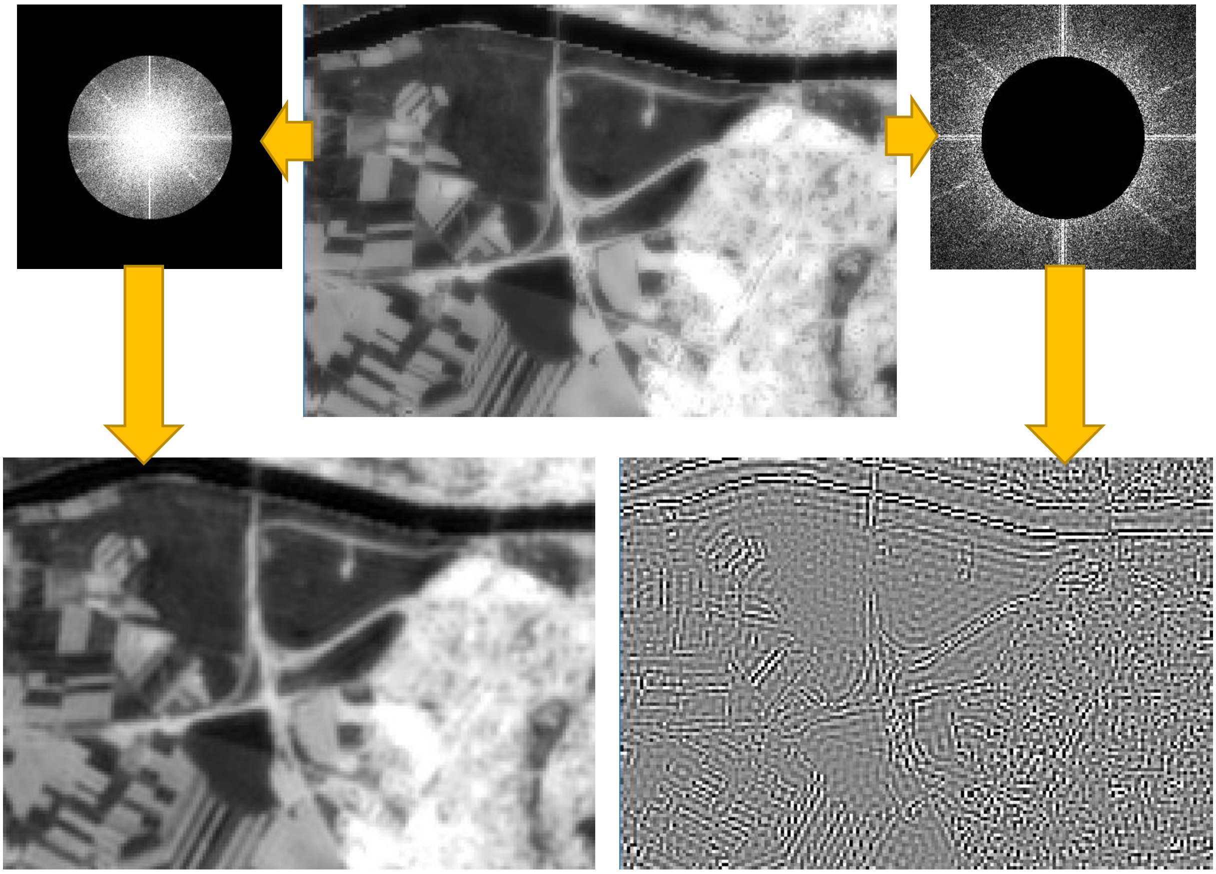


Fig. 4 Temperature image and it's Fourier Amplitude spectrum

Surface temperature imagery, retrieved using Landsat-8 longwave infrared data in frequency domain consist from different spatial frequency components. Longwave components are concentrated in central part of Amplitude spectrum and corresponds to extensive homogenous fields, like lakes, agriculture fields, forests, rivers, etc. Raise of the spatial frequency and its transition closer to borders of amplitude spectrum corresponds to decrement of the distance between surfaces with different temperature. The highest frequencies corresponds to edges between different surfaces represented by low frequency component.



Low frequency component High frequency component

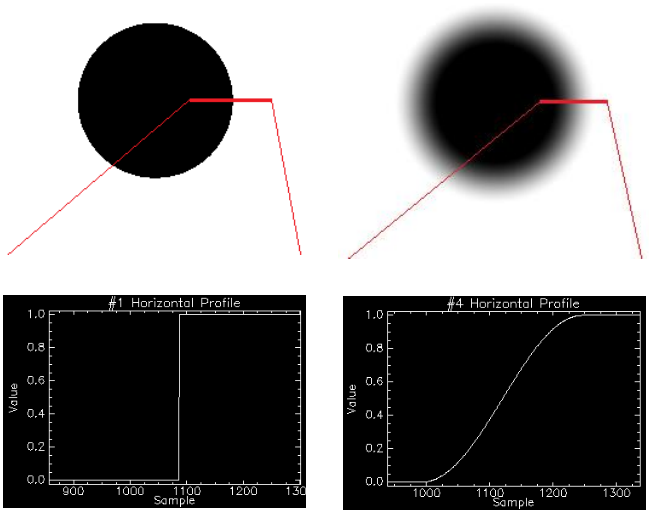
Fig. 5 Extraction of low and high frequency components

Using the suggestion, that contrast edges between different landscape objects remains unchangeable for a long period, imagery pairs of high frequency components distribution becomes the appropriate data for superresolution technique, because its equivalency despite time difference. After estimation of high frequency components distribution data, it merges with low-frequency components, and in result we have enhanced surface temperature data. Each amplitude spectrum value is represented as absolute FFT roots value:

$$A(u,v)=\sqrt{=R_{u,v}^2+I_{u,v}^2} \tag{3}$$

where $A(u,v)$ – amplitude value; $R_{u,v}^2$ – real part of FFT root; $I_{u,v}^2$ – imaginary part of FFT root. As real matrix can not be presented in complex values, Fourier spectrum must be decomposed into matrices of real and imaginary values.

Next step is building of Fourier spectrum filter, which separates low and high frequency components. For both imaginary and real part of spectrum for both of images high-frequency components are need to be extracted for superresolution performance. For this purpose a fuzzy relationship matrices have been built, which allow smooth separation of low and high frequencies. This approach allow selecting the most appropriate and effective separation method.



Threshold low-pass filter Fuzzy low-pass filter

Fig. 6 Threshold and fuzzy filters

Each relationship matrices must meet next requirement:

$$M_{Lo}+M_{Hi}=M_1 \tag{4}$$

where M_{Lo}, and M_{Hi} are low and high frequency relationship matrices respectively, M_1 is all-ones matrix.

Each spectrum multiplies by fuzzy relation matrix with data in the range 0..1, that represents fuzzy relation degree. As the maximum frequency represented by frequency $\frac{1}{2}N$ m^{-1}, where N – images' spatial resolution, the frequency, with 0.5 relation degree to each of components represented by frequency $\frac{1}{4}N$ m^{-1}. Separated high-frequency component were utilized for spatial resolution enhancement technique, and then extracted from resulting images Fourier spectra were merged with low-frequency components of each of the images. Inversed Fast Fourier Transform performs transition from frequency domain into spatial domain.

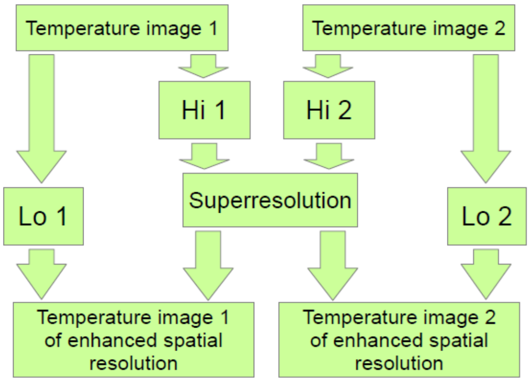


Fig. 7 General flowchart of frequency component merging for imagery spatial resolution enhancement

III. RESULTS AND DISCUSSION

Estimation of the spatial resolution enhancement conducted using modulation transfer function (MTF) of input images and resulting image and its comparison. This technique also help to compare the efficiency of both approaches: threshold separation and fuzzy separation. MTF analysis demonstrated that threshold technique gives nearly 74 % of spatial resolution enhancement [14], relatively to input images. Fuzzy approach 12 % appeared to be more effective, than threshold, which utilizes binary separation logic. Next figure demonstrates visual difference temperature images before and after superresolution processing.

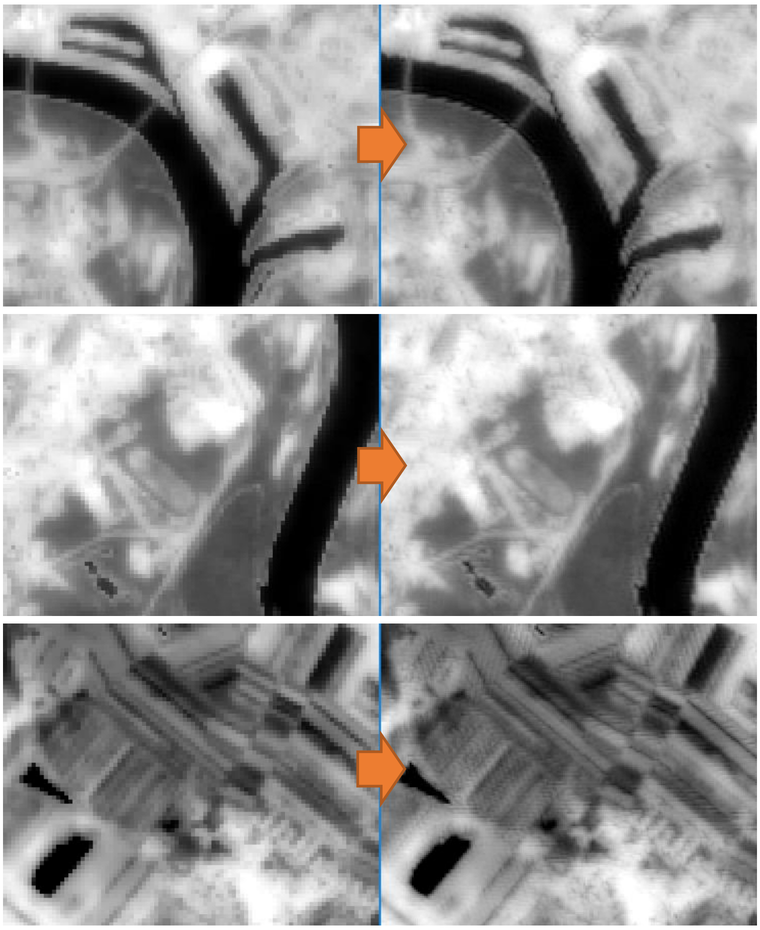


Fig. 8 Comparison between images before (left) and after (right) superresolution processing

According to existing factsheet (https://www.usgs.gov/land-resources/nli/landsat/landsat-9), next Landsat satellite, Landsat-9, would have longwave infrared sensor (TIRS-2) with the same spatial resolution as TIRS, mounted on Landsat-8, and data informativity will remains the same. Proposed improved technique for thermal imagery spatial resolution enhancement is an effective way of processing of available variety of collected Landsat data, starting from 1984. This amount of big data is an appropriate information for detailed temperature imagery long-term time series processing. Results of this processing will help in long-term urbanized areas development and expanding analysis, its effect on public health and environment: ecosystems, natural landscapes and water bodies. In addition, it will be useful for further development planning and expanding.

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