Fusion of Telescopic and Doppler Radar Data

Mirko Navara, Martin Matoušek, Ondřej Drbohlav
{navara,xmatousm,drbohlav}@cmp.felk.cvut.cz

Center for Machine Perception,
Czech Technical University in Prague

Abstract

For observation of satellites and space debris and for measurement of their orbits we combine telescopic images with response of Doppler radars. We use single images from a terrestrial telescope. Our radar is passive, we receive the signal of a distant terrestrial transmitter. The receiver has a *non-directional antenna* and only the *Doppler shift* is used to get information on the object. Due to sensitivity limitations, our approach is applicable to large objects (RCS $\geq 5\,\mathrm{m}^2$) at distances $\leq 2000\ \mathrm{km}$. Our method requires simultaneous detections by a telescope and a radar during the same fly-over, not necessarily at exactly the same time.

Methodology

In telescopic images, LEO objects usually pass through the whole FOV during the exposure, thus we know only a line in the image which contains the projected trajectory. This gives only 2 of 4 parameters of a circular orbit. We try to get the missing parameters from fusion with Doppler radar data. A single signal from the radar at a given time gives us one real variable, admitting to reduce the number of degrees of freedom by 1. To determine a circular orbit (the 2 degrees of freedom missing in the telescopic observation of a LEO object), we can use

- more receivers at different positions,
- longer radar tracking.

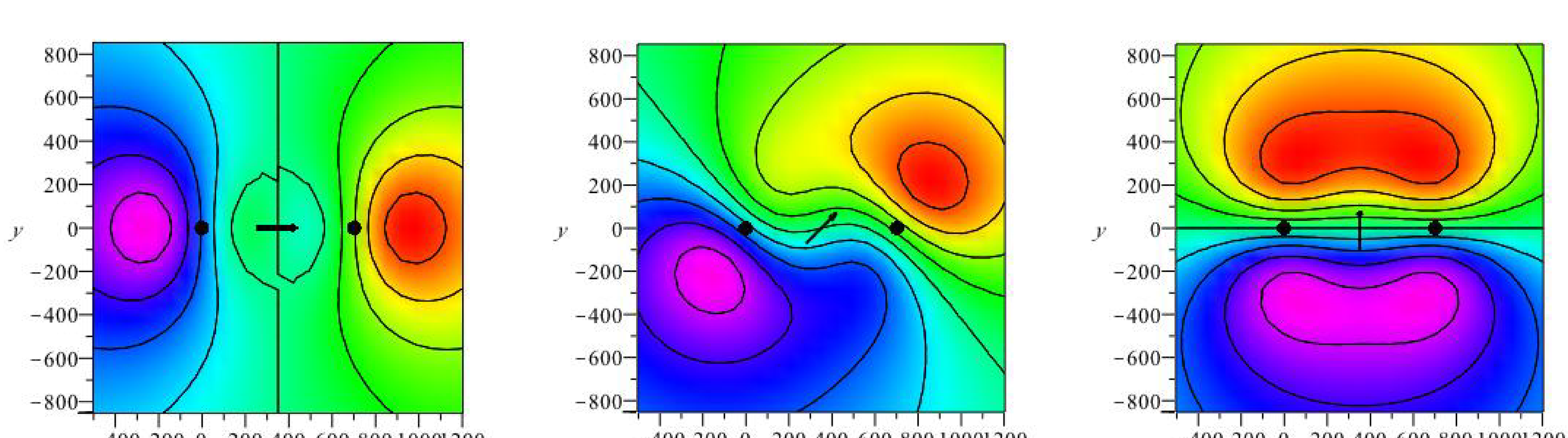
The forward task—the computation of the Doppler shift from a given trajectory—is easy. The inverse task—the computation of a trajectory from the Doppler shifts—is hardly possible because the dependence of radar data on orbital elements is very complex. To fit the orbital elements to radar data, there are too many degrees of freedom. A fusion of radar and telescopic data is still possible.
From Doppler radar data, we estimate

- the height,
- the time when the object passed through the FOV,
- the direction of velocity (its sign).

We start from the initial set of hypotheses, which are all circular trajectories whose projections to the image plane lie in the line detected in the telescopic image. We compute the corresponding Doppler radar responses. Using standard optimization search techniques, we find the best-fitting hypothesis and the corresponding orbital elements. A typical result is in figures showing the sensitivity to the height and time (red line).

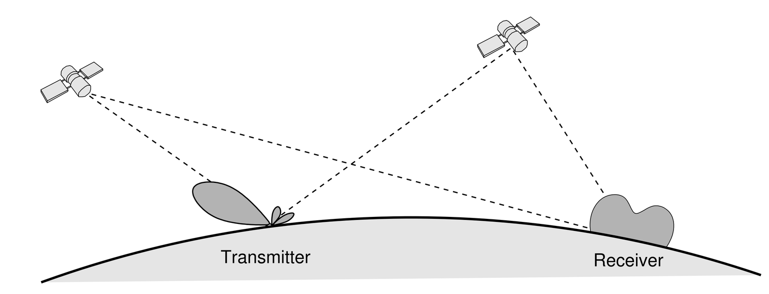
Sensitivity to Height with Given Telescopic Data

Sensitivity of the Doppler shift to height as a function of horizontal position of the object [km] for various directions of velocity (arrows); small disks denote the transmitter and the receiver.



Radar Data

A passive bi-static Doppler radar setup with a terrestrial transmitter and receiver.



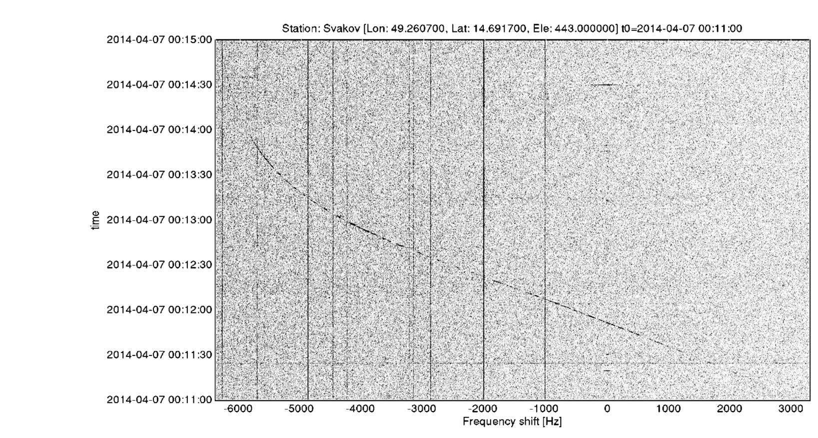
Transmitter:
- signal from GRAVES radar
  (French radar-based space surveillance system)
- $143.050\,\mathrm{MHz}$ continuous wave

Receiver:
- Czech Radio-Astronomers Amateur Network
- $712\,\mathrm{km}$ distance $\rightarrow$ no direct reception

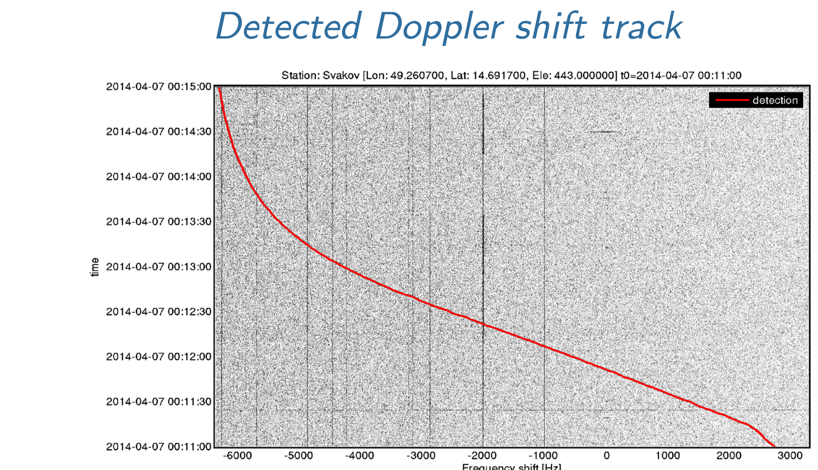
Preprocessing:
- quadrature signal on intermediate frequency
- digitised $2 \times 16\,\mathrm{bit}$ channels @ $48\,\mathrm{kHz}$.
- 2D spectrograms, sliding window FFT,
  $1/3\,\mathrm{s}$ window
- frequency range $\pm 7\,\mathrm{kHz}$ around the carrier
- using the amplitude of the spectrogram only
- accuracy $5\,\mathrm{Hz}$ at $143.05\,\mathrm{MHz}$
  (relative error $3.5 \cdot 10^{-8}$)
- automatic Doppler shift track detection
  (dynamic programming)

We are tracking the Doppler shift of the GRAVES carrier, reflected by a LEO object, which produces the characteristic pattern of Doppler shift. Satellites up to $2000\,\mathrm{km}$ with RCS about $5\,\mathrm{m}^2$ or more are detected.

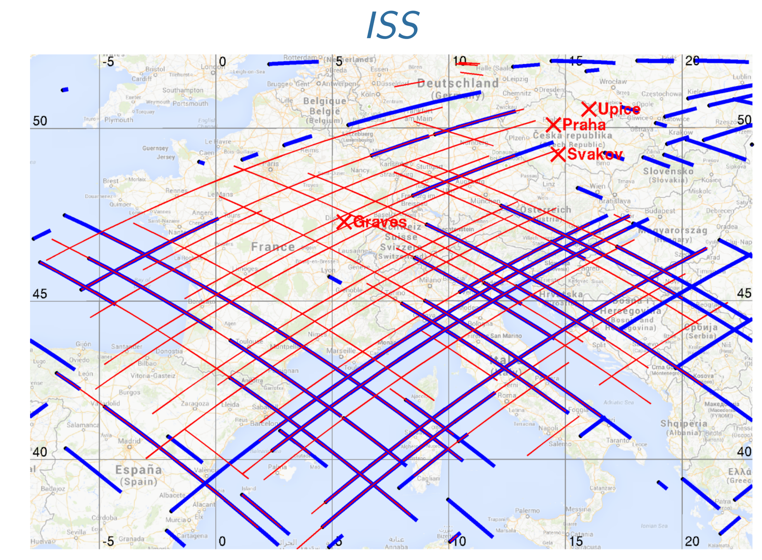
Doppler shift track data



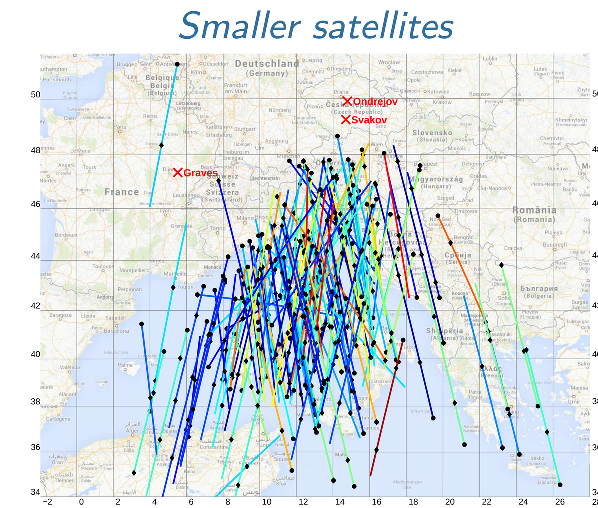
Detected Doppler shift track



ISS



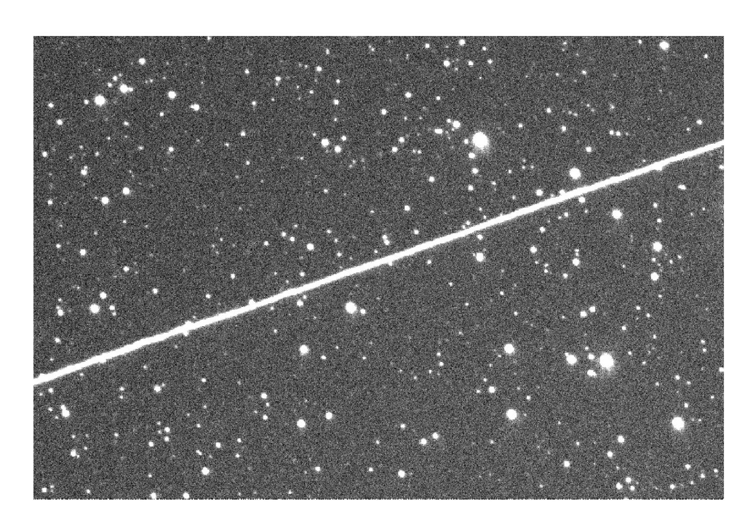
Smaller satellites



We have annotated 189 hours of data; 553 fly-overs of 229 different LEO objects were observed.

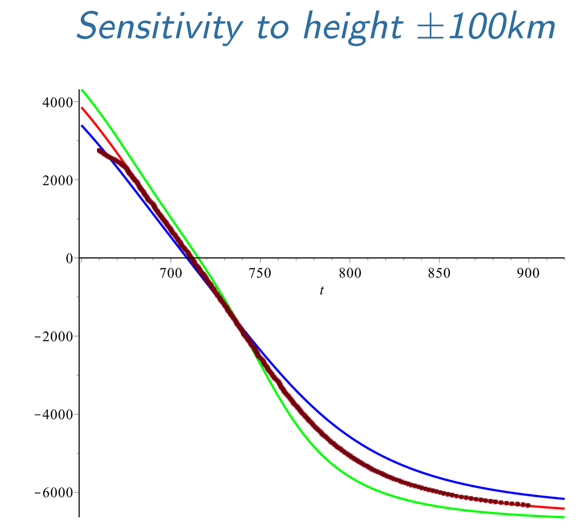
Optical Data

- Ondřejov observatory, Czech Republic
  (N $49.9091°$, E $14.791966°$, $528\,\mathrm{m}$ a.s.l.)
- $60\,\mathrm{cm}$ mirror, FOV $20'$
- CCD camera 1054×1027, 1.177"/pixel.

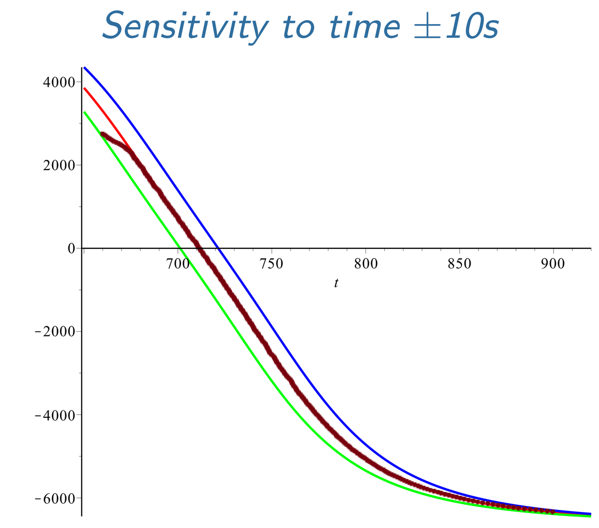


Sensitivity with Given Telescopic Data

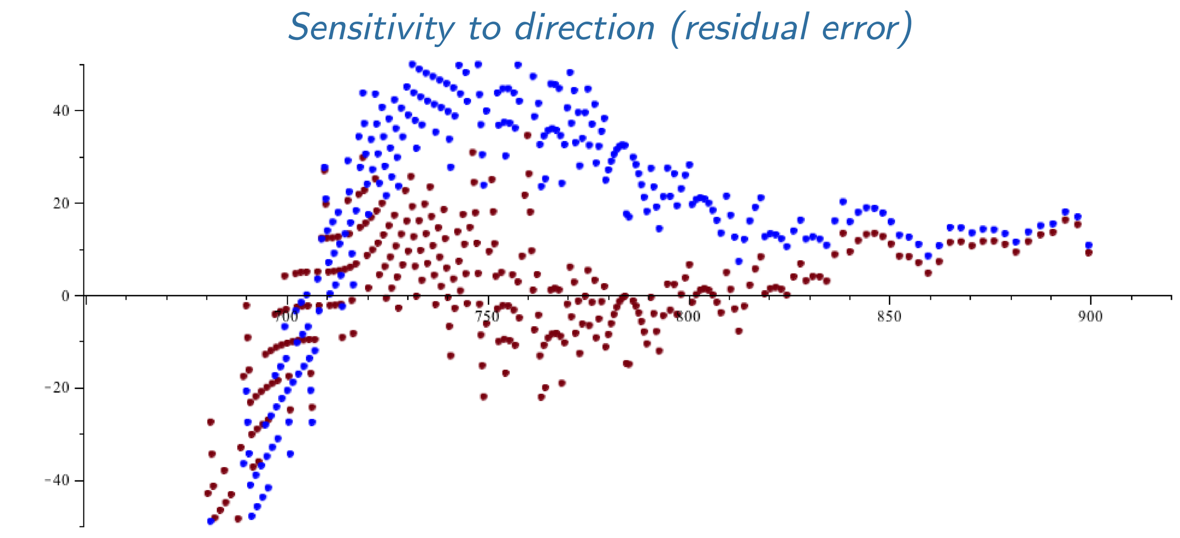
Sensitivity to height ±100km



Sensitivity to time ±10s



Sensitivity to direction (residual error)



Real radar detections (dark red points), the best fit (red line) and simulated response for height/time changed (blue and green).
(horizontal axis: time [s], vertical axis: Doppler shift [Hz])

*Correct vs. **incorrect** sign of velocity.*

Conclusions

There is a good fit among the telescopic image, radar data, and orbital elements from the database. Data from a single radar admit to estimate the missing parameters with a resolution of

- $1\,\mathrm{km}$ in height,
- $0.02°$ in inclination,
- $0.3°$ in RAAN,
- $< 1\,\mathrm{km}$ in mean anomaly at epoch.

Sensitivity analysis and recommendations for the configuration of observations were obtained. In the future, the following steps could improve the results:

- Upgrade of hardware of radar receivers.
- Improve the track detection accuracy, including end points.
- Fusion of data from more radar stations.
- Telescope at a better position. Northern Italy is the best.

References

[1] A Collection of Satellite Database. http://satellitedebris.net, March 2014.

[2] A GRAVES Sourcebook. http://www.fas.org/spp/military/program/track/graves.pdf, Version of 2013-08-07.

[3] Yanagisawa, T., Umehara, H.: Strategy for detection of eccentric objects near the geosynchronous region. *Acta Astronautica* **65** (2009), 1001–1006.

[4] Seitzer, P. et al.: Visible Light Spectroscopy of GEO Debris, *AMOS*, 2012.

[5] Šára, R., Matoušek, M., Franc, V.: RANSACing Optical Image Sequences for GEO and near-GEO Objects. *AMOS*, 2013.

[6] Navara, M., Matoušek, M.: Sensitivity of Doppler radar to orbit parameters. Technical report, Czech Technical University in Prague, 2014.

this poster the paper

Supported by the Missile Defense Agency (USA) and by the Czech Science Foundation.