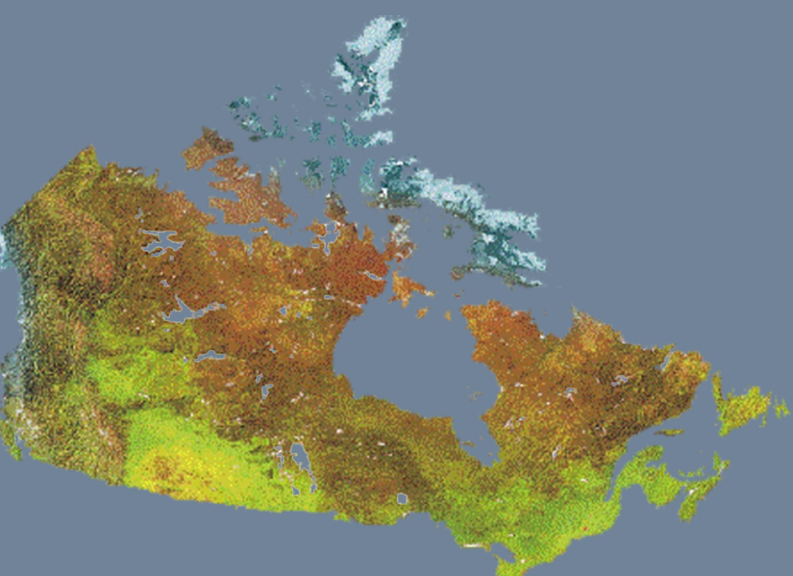


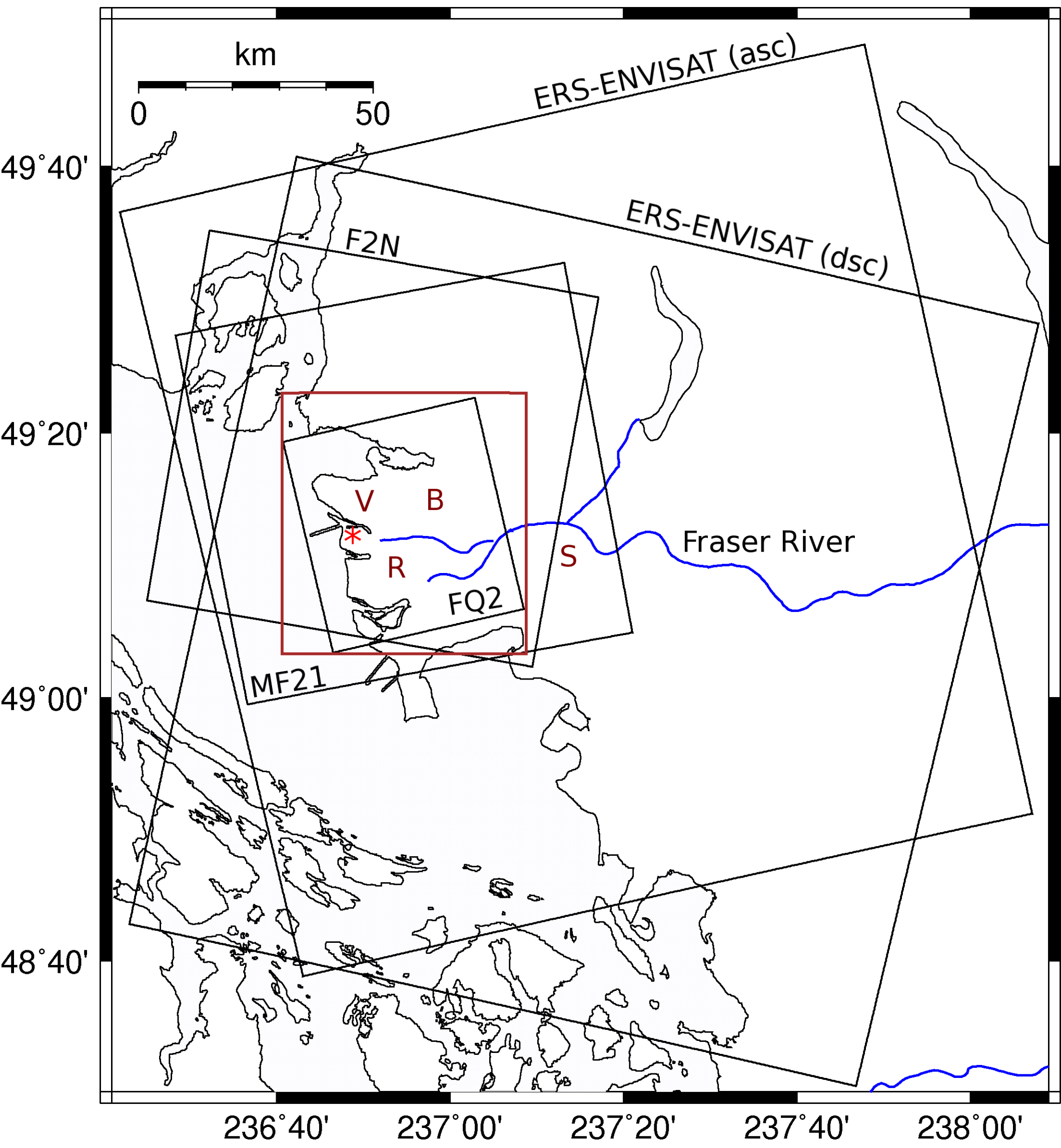
GROUND DEFORMATION OCCURRING IN THE GREATER VANCOUVER REGION, BRITISH COLUMBIA, FROM TWENTY YEARS OF ERS-ENVISAT-RADARSAT-2 INSAR OBSERVATIONS



ABSTRACT

Ground subsidence in the south-western part of British Columbia, the third largest metropolitan area in Canada with over 2.2 millions of inhabitants, was measured using the Multidimensional Small Baseline Subset (MSBAS) advanced Differential Interferometric Synthetic Aperture Radar (DInSAR). The MSBAS (Samsonov and d'Oreye, 2012) software calculates two dimensional time series of ground deformation from multiple DInSAR data sets acquired with various acquisition parameters (e.g. spatial and temporal resolution and coverage, wavelength, azimuth and incidence angles). The two dimensional time series produced here have improved temporal resolution, almost uninterrupted coverage and lower noise. The Synthetic Aperture Radar (SAR) data used in this study consists of seven independent sets: one ascending and one descending ERS-1/2 and ENVISAT frames, together spanning July 1995 - September 2010, and three RADARSAT-2 frames spanning February 2009 - October 2012. During the July 1995 period October 2012 we observed fast ground subsidence with a maximum rate greater than -2 cm/year in the Greater Vancouver region that includes the Fraser River delta and the cities of Burnaby, Richmond, Surrey, and Vancouver. The fastest subsidence was observed beneath the Vancouver International Airport and around agricultural and industrial regions. Rapid sub-centimeter ground deformation also occurred during the summer and fall of 2009-2012. These time series suggest that the subsidence rate at the studied regions does not decrease with time as suggested in previous studies but actually increases. The long term impact of subsidence on infrastructure can be significant and needs to be investigated further.

STUDY AREA IN BRITISH COLUMBIA

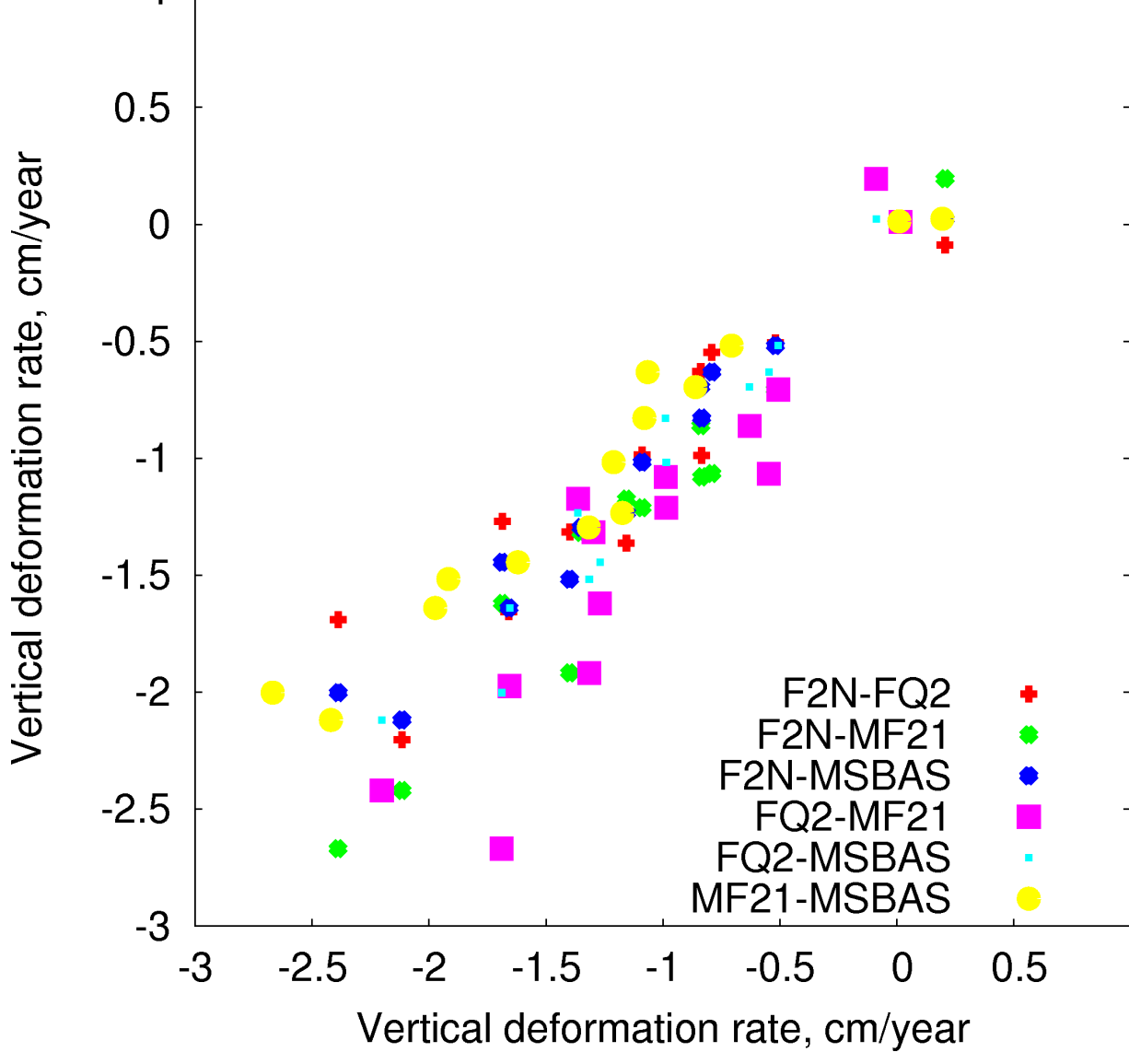


Greater Vancouver region studied here is outlined in brown. In black SAR frames used in this study: RADARSAT-2 Fine Quad 2 (FQ2), Fine 2 Near (F2N), Multi-Look Fine 21 (MF21), and ERS-1/2 and ENVISAT ascending track 392 and descending track 199. Cities: B - Burnaby, R - Richmond, S - Surrey, V - Vancouver. Red star shows location of Vancouver International Airport (YVR).

SAR DATASETS USED IN THIS STUDY

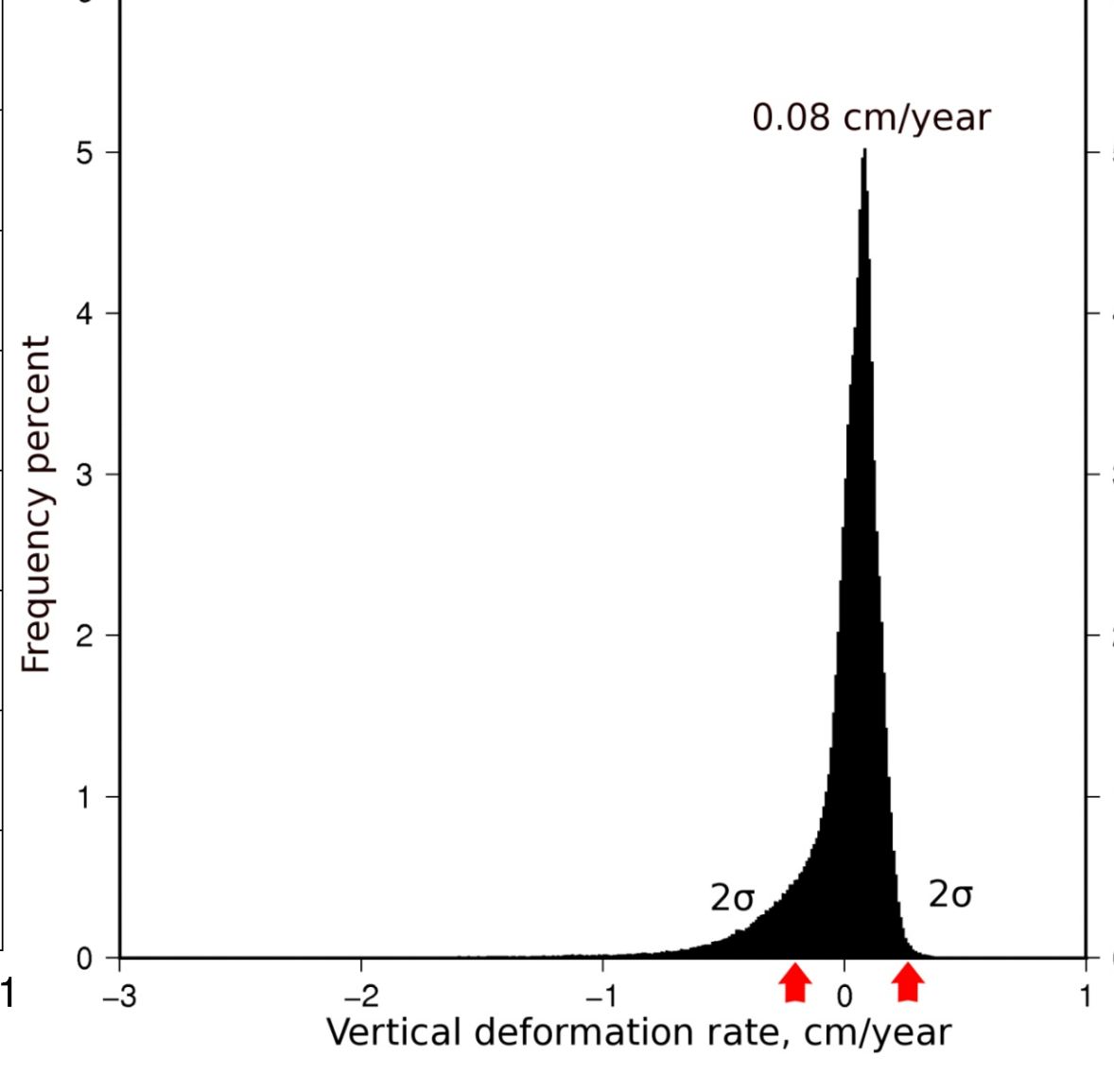
InSAR set	Time span	Resolution, m	θ°	ϕ°	N	M
ERS-ENV (asc)	19950716-20080519	7.8 - 4.0	345	23	27	40
ERS-ENV (dsc)	19921106-20100927	7.8 - 4.0	-165	23	73	291
R2 MF21 (asc)	20100124-20130225	2.7 - 2.9	349	37	33	129
R2 FQ2 (asc)	20090219-20121025	4.7 - 4.9	347	23	47	236
R2 F2N (dsc)	20090321-20121031	4.7 - 5.2	-170	41	38	105
Total:	19950716-20121031				218	801

CORRELATION PLOT

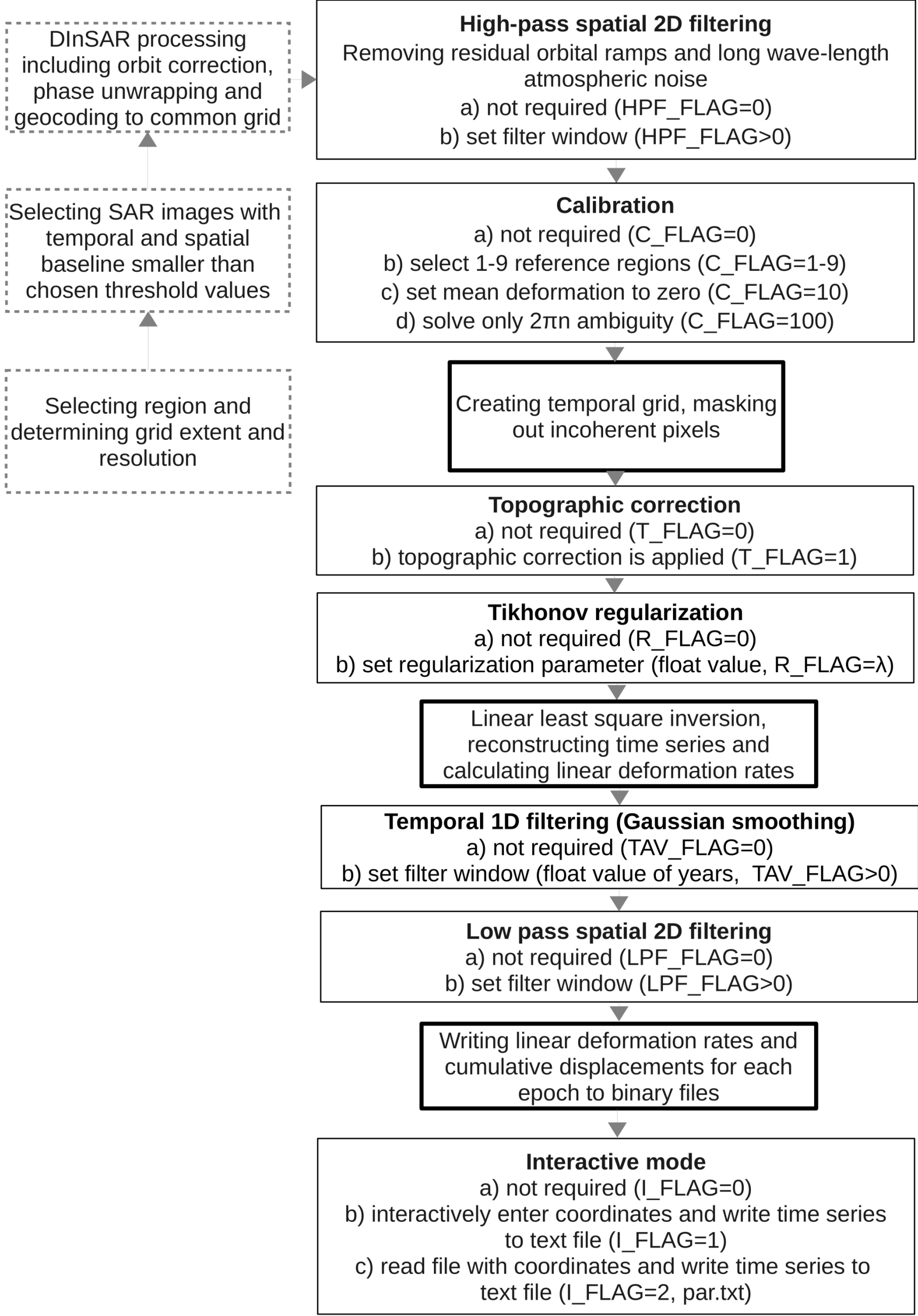


Correlation plots between linear deformation rates normalized by incidence angle ($1/\cos f$), for three independent SBAS linear deformation rates (not shown here) for each RADARSAT-2 frame and vertical component of MSBAS. (b) Histogram of MSBAS vertical deformation rates from, red arrows show 2σ confidence interval, mode of distribution is equal to 0.08 cm/year.}

DEF. RATE HISTOGRAM



MSBAS PROCESSING FLOWCHART



Above: Flowchart diagram of MSBAS processing algorithm. First three processing steps in left column outlined with dashed line are performed outside of this software. The three processing steps outlined with thick line are mandatory and cannot be manipulated. Remaining processing steps outlined with thin boundary can be manipulated by specifying appropriate processing flags (*_FLAG).

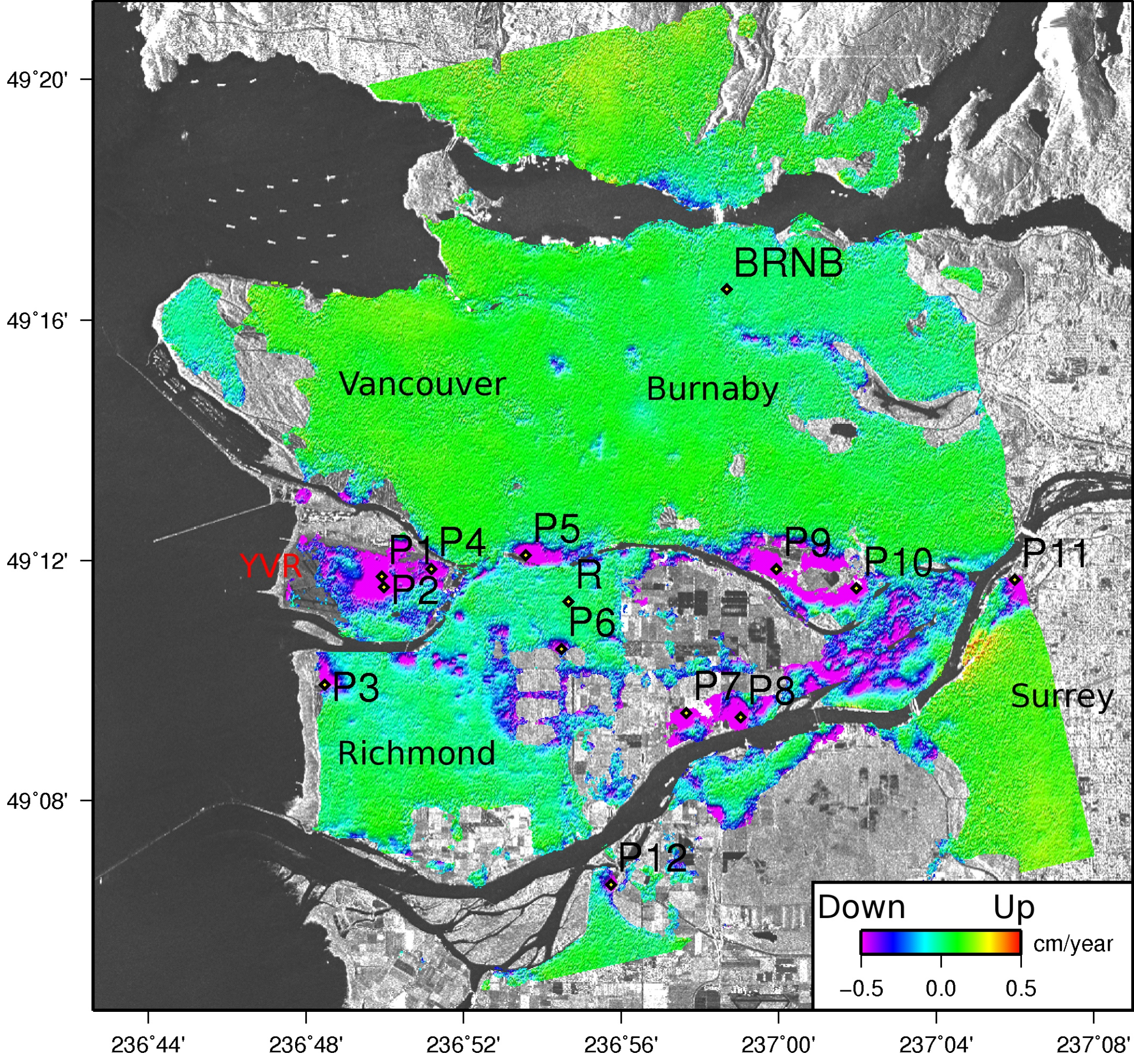
Left: SAR data sets used in this study: ERS-1/2 and ENVISAT ascending track 392 and descending track 199, RADARSAT-2 Multi-Look Fine 21 (MF21), Fine Quad 2 (FQ2), and Fine 2 Near (F2N); time span (in YYYYMMDD format), range-azimuth resolution (extracted from SAR data headers), azimuth T and incidence f angles, number of available SAR images N (206 different acquisition dates), and number of calculated eograms M for each data set.

ERROR ANALYSIS

InSAR sets	Correlation	RMSE, cm/year
ERS-ENV asc - dsc	0.71	0.15
ERS-ENV asc - MSBAS (up)	0.83	0.12
ERS-ENV dsc - MSBAS (up)	0.89	0.10
F2N-FQ2	0.94	0.26
F2N-MF21	0.98	0.23
F2N-MSBAS (up)	0.98	0.15
FQ2-MF21	0.93	0.4
FQ2-MSBAS (up)	0.98	0.13
MF21-MSBAS (up)	0.98	0.3

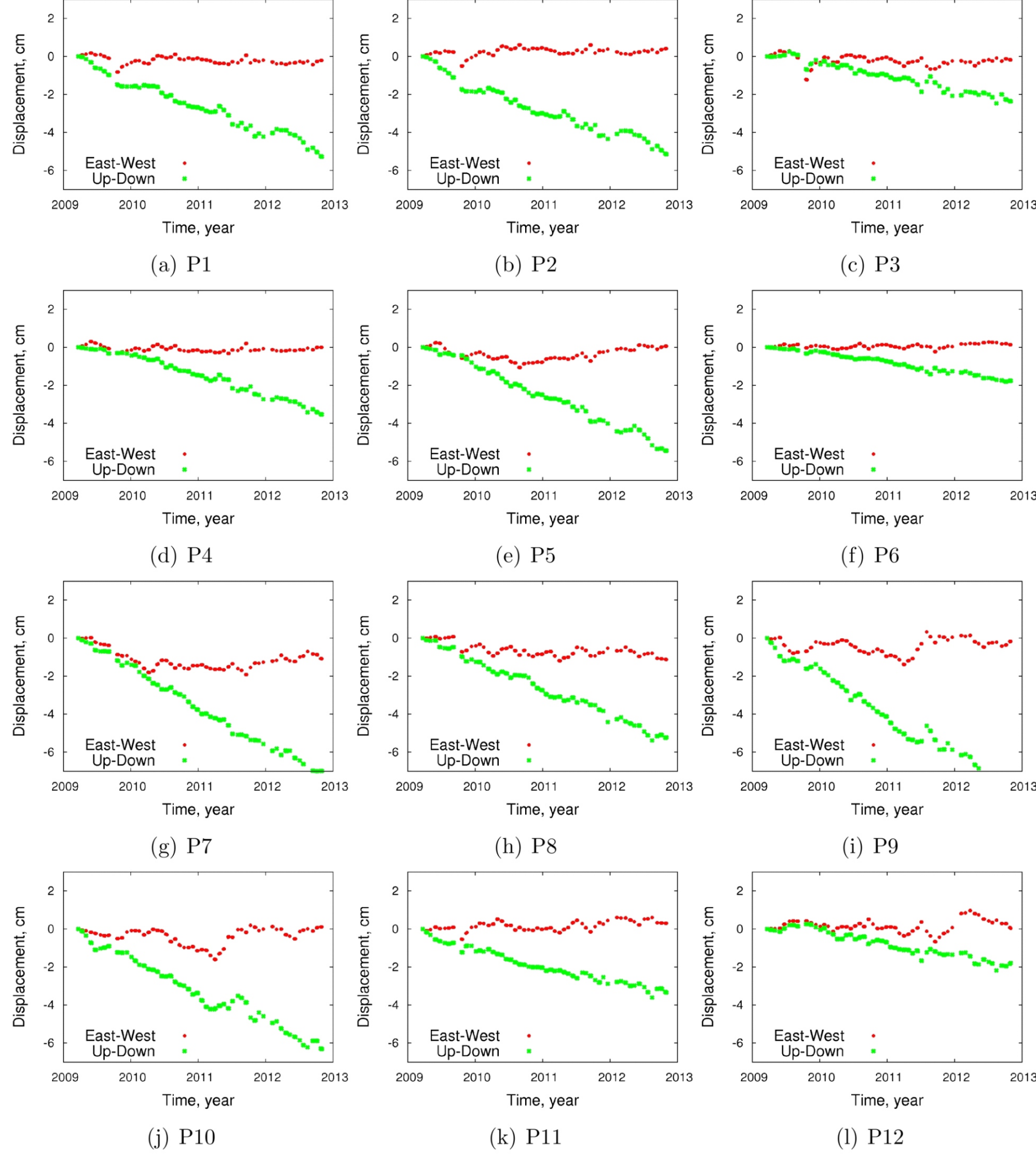
Correlation coefficient and root mean square error (RMSE) between normalized by incidence angle ($1/\cos f$) linear deformation rates for independent SBAS results (not shown here) for each RADARSAT-2 and ERS-ENVISAT beams and vertical component of MSBAS.

2009-2012 VERTICAL LINEAR DEFORMATION RATE RADARSAT-2 DATA



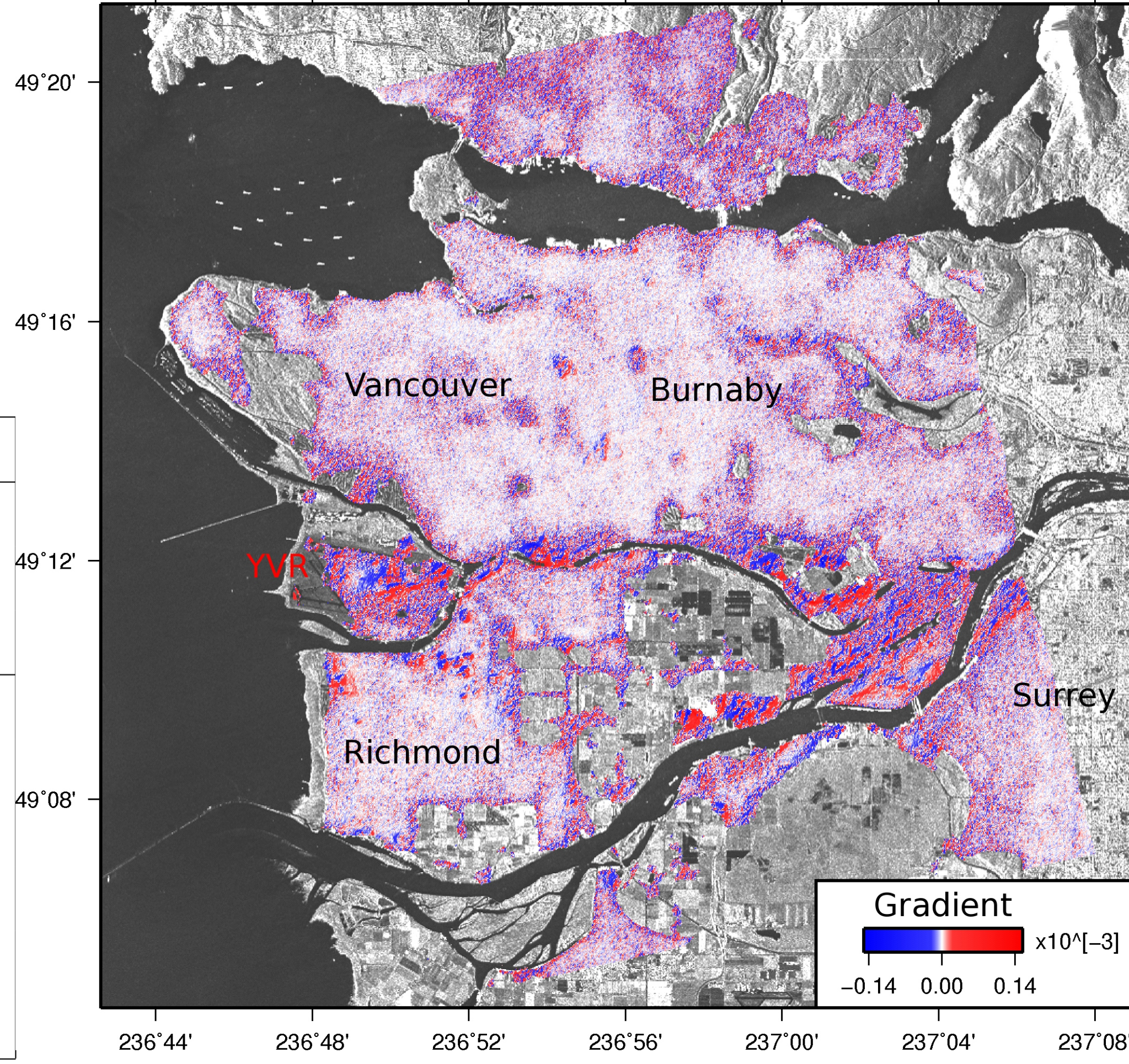
February 2009 - October 2012 RADARSAT-2 (left) and July 1995 - October 2012 ERS-ENVISAT-RADARSAT-2 (right) vertical linear deformation rate calculated with MSBAS technique (Samsonov and d'Oreye, 2012). Subsidence rates were clipped for clarity to maximum values [-0.5;0.5] cm/year. For points P1-P12 and F1-F12 (P implies "partial" and F implies "full" time period) time series of ground deformation are presented below. Cities Burnaby, Richmond, Surrey and Vancouver are shown. BRNB - GPS station, R - reference region considered as stable during MSBAS processing, YVR - Vancouver International Airport.

2009-2012 DEFORMATION TIME SERIES RADARSAT-2 DATA



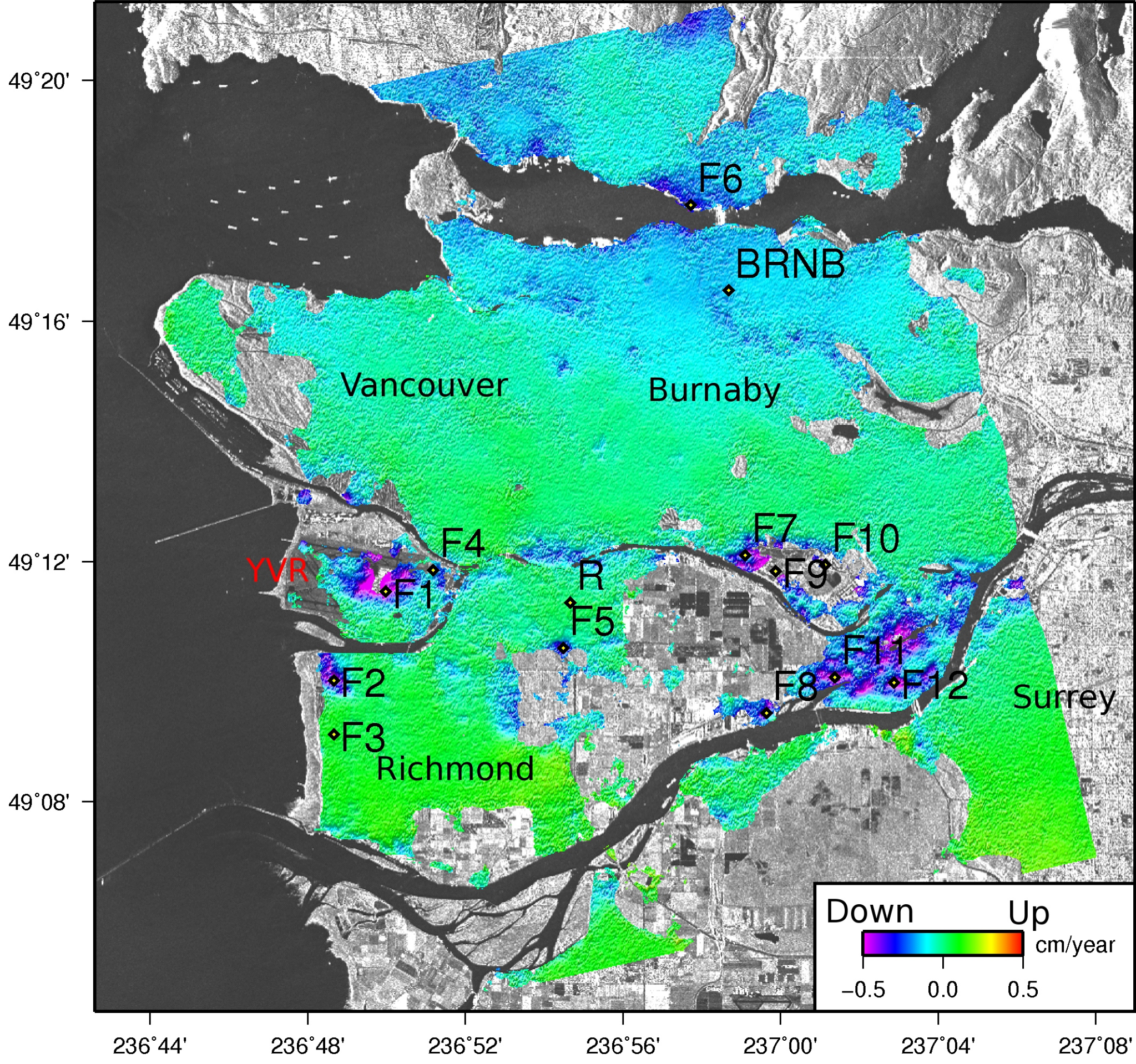
RADARSAT-2 (left) and ERS-ENVISAT-RADARSAT-2 (right) time series of ground deformation calculated for twelve points experiencing fast subsidence. Vertical (in green) and horizontal east-west (in red) time series are shown. Note that points locations vary between two plots.

HORIZONTAL GRADIENT

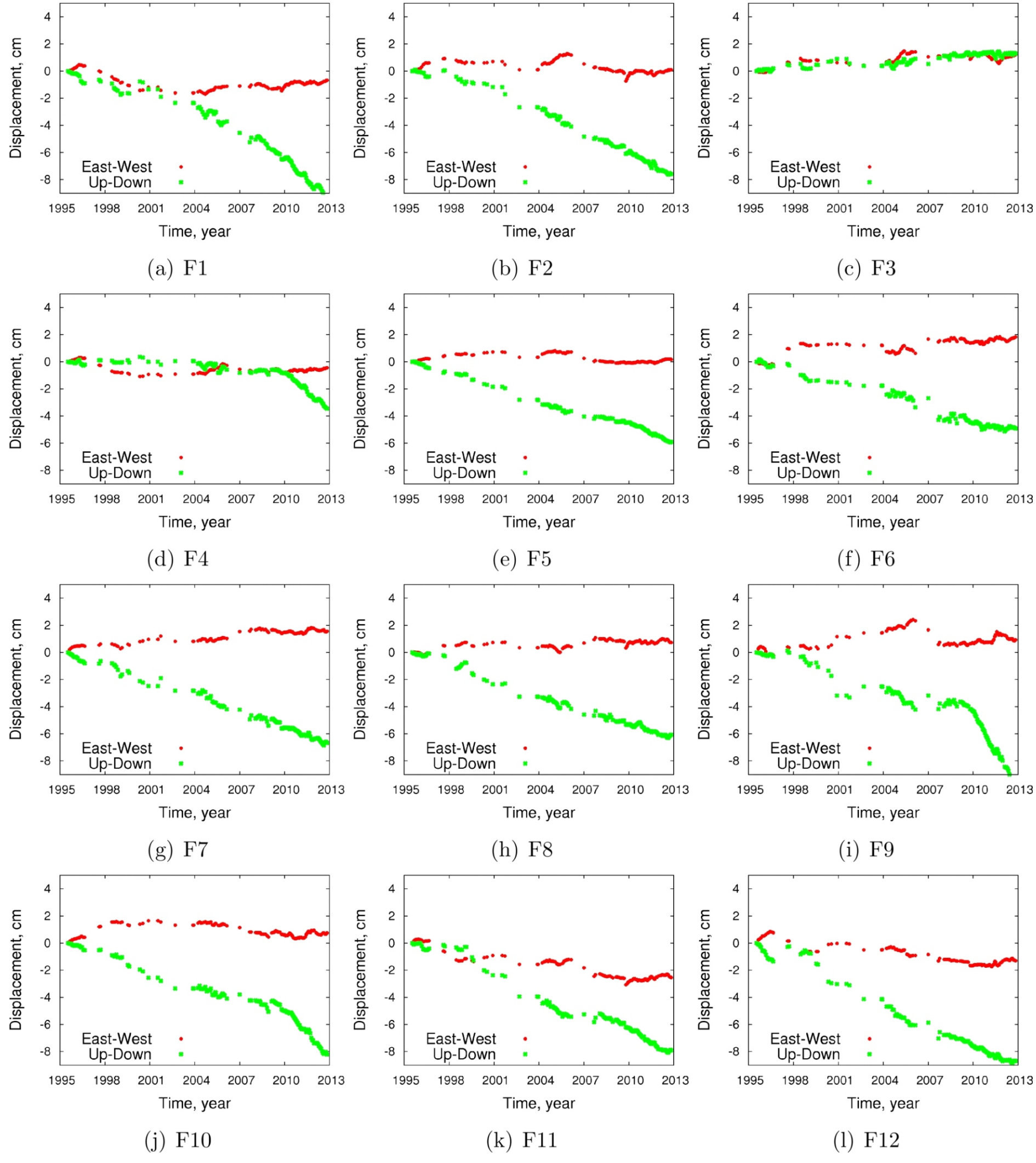


Horizontal gradient of vertical linear deformation rate map calculated from RADARSAT-2 data during February 2009 - October 2012 with MSBAS. Regions of large gradient are susceptible to damage due to ground deformation. Note that a non-linear scale is used.

1995-2012 VERTICAL LINEAR DEFORMATION RATE ERS-ENVISAT-RADARSAT-2 DATA



1995-2012 DEFORMATION TIME SERIES ERS-ENVISAT-RADARSAT-2 DATA



SUMMARY

- Performed processing of ERS-ENVISAT-RADARSAT-2 SAR data spanning 1995-2012 consisting of 218 SLC images and over 800 interferograms.
- Identified localized regions of subsidence with maximum rate 3 cm/year with precision of 0.1-0.4 cm/year or better. Fastest subsidence is observed around the Vancouver International Airport (YVR).
- Time series of ground deformation show steady subsidence during the entire observation period.
- Moderate acceleration of subsidence to a current rate is observed during 2001-2004 around the Vancouver International Airport (YVR).
- Acceleration of subsidence is also observed after 2009 at points P9-P10.
- Sub-centimeter periodic horizontal motion is also observed.
- Horizontal gradient of vertical linear deformation rate identified regions susceptible to damage due to ground deformation.

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