Shuanggen Jin · R. Jin · X. Liu

# GNSS Atmospheric Seismology

## Theory, Observations and Modeling

Springer

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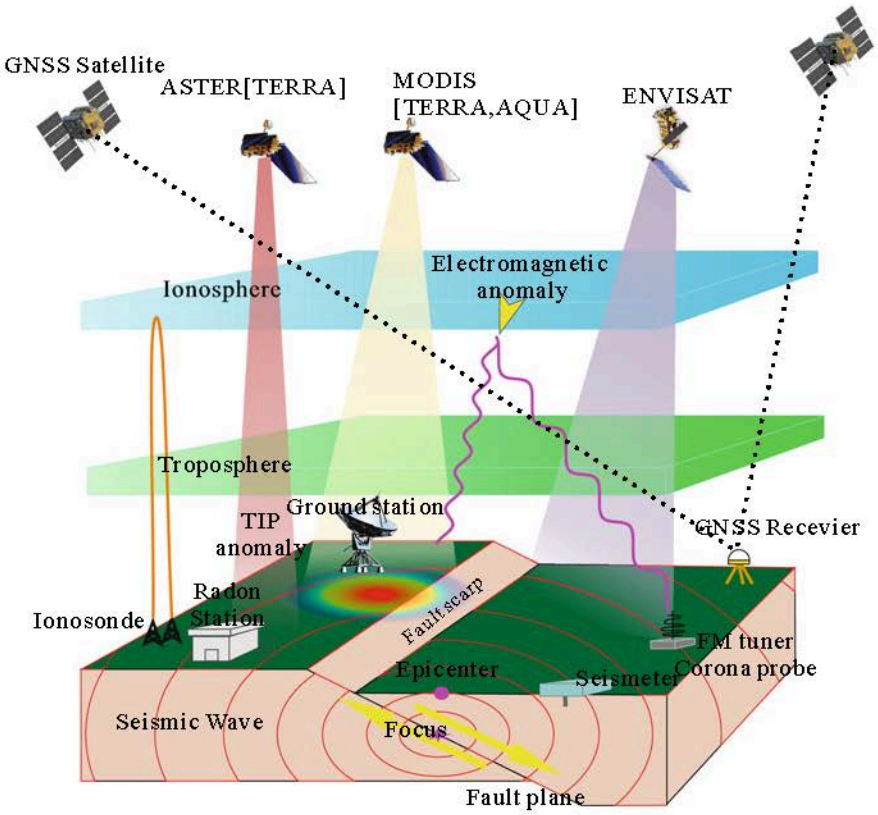
GNSS Satellite
ASTER[TERRA]
MODIS
[TERRA,AQUA]
ENVISAT
Ionosphere
Electromagnetic
anomaly
Troposphere
TIP
anomaly
Ground station
GNSS Recevier
Radon
Station
Ionosonde
Fault scarp
FM tuner
Corona probe
Epicenter
Seismeter
Seismic Wave
Focus
Fault plane

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# Preface

The earthquake is a very complex and broad topic, which is related to various scales motions of the Earth's surface mass and interior as well as the microscopic processes, such as the generation of electric charge and chemical reactions. Also, earthquakes often occur and result in civilian casualties and huge damages as well as secondary disasters, such as tsunami and landslide. Therefore, monitoring and understanding of earthquakes are still a major objective for many countries. The worldwide seismometers could estimate rapidly the location, the magnitude, and the focal mechanism of earthquakes, but the detailed rupture and pre-seismic anomalies are still not clear due to the lack of dense near-field observations and limited observations. Global Navigation Satellite Systems (GNSS), Interferometric Synthetic Aperture (InSAR), seismometer, and gravity measurements could provide unique insights on the size and rupture of the earthquake. However, understanding and prediction of earthquakes are still challenging or difficultly confirmed from traditional technique observations. Nowadays, seismic atmospheric disturbance observations may help us to get a more comprehensive and profound knowledge on the Earth's atmospheric response to the earthquake, volcano, tsunami, and solid Earth/ionosphere coupling, e.g., ionospheric or electromagnetic observations.

GNSS is a powerful tool not only for the crust deformation but also the seismic atmospheric–ionospheric variations, especially for regions with dense GNSS continuous operating stations. The neutral atmospheric parameters and ionospheric Total Electron Content (TEC) can be precisely estimated from ground-based GNSS and spaceborne GNSS Radio Occultation, which can be used to investigate the seismic atmospheric–ionospheric disturbances and may provide insights on the earthquake. Recently, several significant seismic ionospheric disturbances were observed from continuous GPS measurements with acoustic waves, Rayleigh wave, and gravity waves, e.g., the 2011 Mw = 9.1 Japan earthquake. The seismic ionospheric disturbances are probably driven by the ground-coupled airwaves from ground vertical motion of seismic waves propagating. Some mechanism on atmospheric/ionospheric anomalies and coupling processes between the atmosphere and solid Earth were also discussed. Furthermore, some pre-seismic atmospheric and ionospheric anomalies with several hours to several days before the main shock

onset were also observed in the temperature, TEC, and NmF2 time series. Therefore, GNSS may provide us a new perspective to monitor and understand the earthquake with seismic atmospheric–ionospheric disturbances.

However, the detailed pattern, evolution, and mechanism of the seismic ionospheric disturbance are not clear together with earthquake sources. The relationship between the earthquake and the atmospheric–ionospheric variation is not understood comprehensively up to now. The earthquake threshold and pre-seismic ionospheric disturbances following earthquakes with different magnitudes, focal mechanism, depth, and external conditions are still challenging as well as the mechanism of solid Earth/ocean–atmosphere–ionosphere coupling, which needs to be improved for more cases and be verified with more GNSS measurements. This book presents GNSS atmospheric seismology with some recent progresses.

*GNSS Atmospheric Seismology: Methods, Observations and Modelling*, has been written as a monograph and textbook that guides the reader through the theory and practice of seismic atmospheric disturbances sounding as well as possible applications. This book includes Chap. 1: Introduction, Chap. 2: Atmospheric Changes and Observations, Chap. 3: GNSS Tropospheric Sounding, Chap. 4: GNSS Ionospheric Sounding, Chap. 5: Detection Methods for Ionospheric Disturbances, Chap. 6: Seismic Lower Atmospheric Anomalies, Chap. 7: Pre-seismic Ionospheric Anomalies, Chap. 8: Co-/Post-seismic Ionospheric Disturbances, Chap. 9: Two-Mode Seismo-ionospheric Disturbances, Chap. 10: Seismo-ionospheric Rayleigh Waves, Chap. 11: Epicenter from Ionospheric Disturbances, Chap. 12: Tsunami Ionospheric Disturbances, Chap. 13: Volcano Atmospheric Disturbances, Chap. 14: Volcanic Plumes Detection from GNSS SNR, and Chap. 15: Summary and Prospective. Chapters 1–4, 6–10 and 12–15 were contributed from Prof. Shuanggen Jin, Chaps. 5 and 11 and part of Chaps. 8 and 10 were contributed from R. Jin, Chaps. 12 and 13 were contributed from X. Liu, Chap. 14 was contributed from Qinyun Zhang, and part of Chap. 10 was contribute from Yuhan Liu as well as part of Chaps. 6 and 7 from Munawar Shah.

This book presents the theory, methods, results, and modeling of GNSS atmospheric seismology for scientists and users who have basic background and experiences in GNSS and seismology. Furthermore, it is also useful for the increasing number of next generation multi-GNSS scientists, engineers, and users' community as well as hazards mitigation and reduction. We would like to thank Assistant Editor's help and Springer-Verlag for their cordial collaboration and help during the process of publishing this book.

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# Contents

## Part II Seismic Atmospheric Disturbances

# Abbreviations

| | |
|---|---|
| ABL | Atmospheric Boundary Layer |
| AGW | Acoustic Gravity Wave |
| ART | Algebraic Reconstruction Technique |
| ASTER | Advanced Spaceborne Thermal Emission and Reflection Radiometer |
| AVHRR | Advanced Very High Resolution Radiometer |
| AVO | Alaska Volcano Observatory |
| BDS | BeiDou Navigation Satellite System |
| BPR | Bottom Pressure Records |
| C/A | Coarse/Acquisition |
| CAS | Chinese Academy of Sciences |
| CDMA | Code Division Multiple Access |
| CEA | China Earthquake Administration |
| CHAMP | Challenging Mini-satellite Payload |
| CID | Co-seismic Ionospheric Disturbances |
| CIT | Computerized Ionospheric Tomography |
| CMONOC | Crustal Movement Observation Network of China |
| CMT | Centroid Moment Tensor |
| CODE | Center for Orbit Determination in Europe |
| COSMIC | Constellation Observing System for Meteorology, Ionosphere, and Climate |
| CYGNSS | CYclon GNSS |
| DART | Deep-ocean Assessment and Reporting of Tsunamis |
| DCB | Differential Code Biases |
| DD | Double Difference |
| DEMETER | Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions |
| DGPS | Differential GPS |
| DOT | Department of Transportation |
| DOY | Day of Year |

| | |
|---|---|
| Dst | Disturbance storm time |
| ECMWF | European Centre for Medium-Range Weather Forecasts |
| EIA | Equatorial Ionization Anomaly |
| EISCAT | European Incoherent Scatter Scientific Association |
| ENVISAT | ENVIronmental SATellite |
| ESA | European Space Agency |
| EST | Equivalent Slab Thickness |
| EU | European Union |
| FDMA | Frequency Division Multiple Access |
| FDSN | International Federation of Digital Seismograph Networks |
| FDTD | Finite Difference Time Domain |
| FFT | Fast Fourier Transform |
| GAGAN | GPS-Aided Geo Augmented Navigation |
| Galileo | Galileo Navigation Satellite System |
| GAMIT | GPS analysis software by Massachusetts Institute of Technology |
| GBAS | Ground-Based Augmentation Systems |
| GDOP | Geometric Dilution of Precision |
| GEO | Geostationary Earth Orbit |
| GEONET | GPS Earth Observation Network in Japan |
| GFZ | GeoForschungsZentrum Potsdam |
| GIM | Global Ionospheric Map |
| GIPSY-OASIS | GNSS-Inferred Positioning System and Orbit Analysis |
| GLONASS | GLOnass NAvigation Satellite System of Russia |
| GMF | Global Mapping Function |
| GNSS | Global Navigation Satellite Systems |
| GNSS-R | GNSS-Reflectometry |
| GO | Geometric Optics |
| GOCE | Gravity Field and Steady-State Ocean Circulation Explorer |
| GPS | Global Positioning System |
| GPS/MET | GPS/Meteorology |
| GRACE | Gravity Recovery and Climate Experiment |
| GSI | Geographical Survey Institute in Japan |
| GSN | Global Seismographic Network |
| GTS | Global Telecommunication System |
| HFI | Hardy Function Interpolation |
| IAG | International Association of Geodesy |
| IERS | International Earth Rotation and Reference System Service |
| IGS | International GNSS Service |
| IGW | Internal Gravity Wave |
| InSAR | Interferometric Synthetic Aperture Radar |
| IPP | Ionosphere Pierce Point |
| IRI | International Reference Ionospheric |
| IRIS | Incorporated Research Institutions for Seismology |
| IRNSS | India's Regional Navigation Satellite Systems |
| ISR | Ionospheric Scatter Radar |

| | |
|---|---|
| ITRF | IERS Terrestrial Reference Frame |
| JMA | Japan Meteorological Agency |
| JPL | Jet Propulsion Laboratory |
| LAAS | Local Area Augmentation System |
| LC | Linear Combination |
| LEO | Low Earth Orbit (satellite) |
| LiDAR | Light Detection And Ranging |
| LOS | Line of Sight |
| LS | Least Squares (adjustment) |
| LST | Land surface temperature |
| LT | Local Time |
| MART | Multiplicative Algebraic Reconstruction Technique |
| MDA | Maximum Disturbance Azimuth |
| MDD | Maximum Disturbance Distance |
| MDP | Maximum Disturbance Point |
| MEO | Medium Earth Orbit |
| mHz | milli-Hertz |
| MIT | Massachusetts Institute of Technology |
| MODIS | MODerate-resolution Imaging Spectroradiometer |
| MSS | Mean of the Square Slopes |
| NASA | National Aeronautics and Space Administration |
| NCAR | National Center for Atmospheric Research |
| NGDC | US National Geophysical Data Center |
| NMF | Niell Mapping Function |
| NOAA | National Oceanic and Atmospheric Administration |
| NWP | Numerical Weather Prediction |
| OBSIP | Ocean Bottom Seismograph Instrument Pool |
| OLR | Outgoing Long-wave Radiation |
| OMI | Aura/Ozone Monitoring Instrument |
| PASSCAL | Portable Array Seismic Studies of the Continental Lithosphere |
| PBO | Plate Boundary Observatory |
| PNT | Positioning, Navigation and Timing |
| POD | Precise Orbit Determination |
| PPP | Precise Point Positioning |
| PRN | Pseudo-Random Noise |
| PWV | Precipitable Water Vapor |
| QOA | Quasi-Optimum Algorithm |
| QZSS | Quasi-Zenith Satellite System |
| RINEX | Receiver Independent Exchange |
| RMS | Root Mean Square |
| RO | Radio Occultation |
| RTK | Real-Time Kinematic |
| SAC-C | Satellite de Aplicaciones Cientificas-C |
| SD | Single Difference |
| SHAO | Shanghai Astronomical Observatory |

| | |
|---|---|
| SID | Seismic Ionospheric Disturbance |
| SIP | Sub-ionospheric Pierce Points |
| SLM | Single Layer Model |
| SNR | Signal-to-Noise Ratio |
| SPIDR | Space Physics Interactive Data Resource |
| STD | Slant Tropospheric Delay |
| STEC | Slant Total Electron Content |
| SVD | Singular Value Decomposition |
| TEC | Total Electron Content |
| TECU | Total Electron Content Unit |
| TID | Traveling Ionospheric Disturbances |
| TIE-GCM | Thermosphere–Ionosphere–Electrodynamics General Circulation Model |
| UHF | Ultra High Frequency |
| UNAVCO | University NAVSTAR Consortium |
| USGS | US Geological Survey |
| UT | Universal Time |
| UTC | Coordinated Universal Time |
| VEI | Volcanic Explosivity Index |
| VHF | Very High Frequency |
| VMF | Vienna Mapping Functions |
| WGS | World Geodetic System |
| WVR | Water Vapor Radiometry |
| ZHD | Zenith Hydrostatic Delay |
| ZTD | Zenith Tropospheric Delay |
| ZWD | Zenith Wet Delay |