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Enhancıng Dısaster Response Operatıons wıth GNSS Applıcatıons

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Abstract

The frequency and severity of natural disasters have significantly increased over the last few decades as a result of rapid urbanization, environmental degradation, and climate change. These complex emergencies demand a multidisciplinary, technology-driven approach to enhance preparedness, response, and recovery. Global Navigation Satellite Systems (GNSS) — including GPS (United States), GLONASS (Russia), Galileo (European Union), and BeiDou (China) — have emerged as vital tools in modern disaster management operations. GNSS enables high-precision positioning, timing, and navigation, allowing first responders and emergency managers to coordinate effectively in real-time. GNSS satellites continue their activities in space freely within the scope of Article I of the Outer Space Treaty.

This study examines how GNSS technologies are used globally to enhance disaster response operations, and then compares these international applications with Turkey's national framework under the Disaster and Emergency Management Authority (AFAD). This study also highlights the importance of space law.Through a comprehensive review of case studies, best practices, and performance analyses, this paper identifies both opportunities and challenges associated with GNSS implementation. It aims to provide strategic insights for strengthening national disaster resilience through improved integration of satellite-based geospatial intelligence. Globally, GNSS-supported systems like Japan's GEONET and the United States' FEMA GPS networks have proven invaluable for monitoring hazards and coordinating rapid interventions. In Turkey, initiatives such as the TUSAGA-Aktif (CORS-TR) network, AYDES Information System, and AFAD's mobile GNSS tools have created a resilient geospatial infrastructure. These systems enable centimeter-level accuracy for rapid damage assessment, resource tracking, and real-time field coordination.

Ultimately, the findings highlight the necessity of combining GNSS with complementary technologies such as Geographic Information Systems (GIS), Remote Sensing (RS), and Unmanned Aerial Vehicles (UAVs) to achieve a comprehensive, data-driven disaster management ecosystem. The paper concludes by recommending policy measures and capacity-building strategies for Turkey and similar developing nations to enhance GNSS utilization for effective disaster response.

Keywords
Space, GNSS, Disasters, Space Law

Introduction

Global Navigation Satellite Systems (GNSS) are relatively rare space-based systems, as only a limited number of countries possess and operate them. Currently, the countries and organizations that have their own GNSS include the United States of America, Russia, the European Space Agency, China, Japan, and India. Other countries either conduct research and development activities to establish their own GNSS or function solely as users of existing systems operated by these major GNSS providers [1].

Türkiye is a relatively new participant in space systems, particularly in the fields of remote sensing and GNSS technologies. Since the 1980s, Türkiye has been launching telecommunications satellites under the Türksat program from foreign spaceports. However, Türkiye does not yet have an independent GNSS satellite constellation in orbit. Consequently, daily civilian applications in the country primarily rely on the Global Positioning System (GPS) operated by the United States, such as navigation and address determination during vehicle use.

In addition to civilian applications, GNSS plays a crucial role in public authorities, especially in civil defense and disaster management operations. For instance, GNSS technologies are essential for locating missing persons in forests, rescuing lost mountain climbers in mountainous terrain, and conducting search-and-rescue operations during foggy conditions or nighttime. As demonstrated by these examples, GNSS is of vital importance in many disaster and emergency scenarios.

Türkiye is frequently exposed to various natural disasters, including earthquakes, floods, forest fires, landslides, and avalanches. Moreover, with a population of approximately 82 million, the country experiences significant traffic congestion, a high number of traffic accidents, and numerous emergency situations. Therefore, the effective use and potential development of GNSS technologies are critically important for Türkiye in terms of public safety, disaster response, and emergency management [2].

Useful Areas of Global Navigation Satellite Systems

To determine the position of an object or a person, signals from at least four navigation satellites in space are required. Three satellites are used to determine the three-dimensional position, while a fourth satellite is required to correct the receiver's clock bias.

The primary application areas of GNSS include measurement of field boundaries, mapping, route determination for land, sea, and air vehicles, and missile detection in military applications. In addition, GNSS plays a critical role in search and rescue operations for missing persons, as well as in detecting and monitoring the displacement of land masses during earthquakes.

Countries that operate GNSS systems provide satellite data to other user countries, such as Türkiye. In some cases, these data are provided free of charge, while in other cases they are subject to a usage fee. In particular, the Global Positioning System (GPS) operated by the United States of America is freely available for civilian users and is widely used in applications such as Google Maps.

The Use of Global Navigation Satellite Systems in Disasters and Emergency Situations

There are a lot of emergency situations in Türkiye for using GNSS systems. Global Navigation Satellite Systems (GNSS) are widely used in a broad range of disaster and emergency situations due to their ability to provide accurate positioning, navigation, and timing information. In natural disasters such as earthquakes, GNSS is utilized to detect and monitor crustal and land surface displacements, enabling the analysis of coseismic and post-seismic deformations. During floods, landslides, avalanches, and forest fires, GNSS supports the mapping of affected areas and facilitates the navigation and coordination of emergency response teams. Furthermore, GNSS plays a critical role in search and rescue operations, particularly in locating missing persons in mountainous, forested, or remote regions under adverse weather conditions. In addition to natural hazards, GNSS is extensively applied in traffic accidents and air, sea, and land transportation emergencies by enabling rapid route determination and efficient deployment of emergency services. Owing to these capabilities, GNSS constitutes an essential technological component in modern emergency and disaster management systems [3].

In this context, the Disaster and Emergency Management Authority of Türkiye (AFAD) utilizes data related to disasters and emergency situations. However, AFAD does not develop GNSS technologies directly; instead, GNSS technology development and scientific research are primarily conducted by universities. These universities provide GNSS data and analyses to AFAD for disaster monitoring and emergency response purposes.

Several academic institutions, such as Istanbul Technical University and Middle East Technical University, actively manage GNSS applications related to disasters and emergency situations. Consequently, AFAD collaborates closely with these universities during disaster events to ensure accurate positioning, deformation monitoring, and situational awareness.

Another key institution in this field is the Scientific and Technological Research Council of Türkiye (TÜBİTAK). Through its space research organization, TÜBİTAK Space (TÜBİTAK UZAY), Türkiye is involved in satellite development, launch activities, and space-based data analysis. Although Türkiye does not currently operate its own GNSS satellite system, TÜBİTAK Space conducts research using GNSS data obtained from satellites operated by other countries. These studies contribute to satellite data analysis, space research, and the advancement of national technological capabilities.

The TUSAGA-Aktif System: A National GNSS Infrastructure for High-Precision Positioning and Scientific Applications

The Turkish National Active GNSS Network—TUSAGA-Aktif—provides an advanced real-time positioning infrastructure that supports centimeter-level accuracy for geospatial, engineering, and scientific applications. Operated jointly by the General Directorate of Land Registry and Cadastre and the General Command of Mapping, the system enhances Türkiye's geodetic capabilities and fosters research across geoscience, remote sensing, and earth deformation studies. This article examines the technical framework, operational principles, and scientific potential of TUSAGA-Aktif within contemporary Global Navigation Satellite System (GNSS) networks. The TUSAGA-Aktif System, completed in 2009 under a TÜBİTAK-supported public R&D initiative, represents Turkey's national GNSS reference network. With over 160 permanent GNSS stations distributed across Türkiye and Northern Cyprus, it delivers correction data for real-time positioning and supports post-processing scientific analyses [5-9].

Technical Structure and Operation

Network Architecture

The infrastructure consists of fixed GNSS receivers strategically installed across the country. Each station continuously collects GNSS signals, including those from GPS, GLONASS, Galileo, and potentially other constellations. These data streams are transmitted to central control and analysis centers integrated within national geospatial agencies.

Real-Time Kinematic (RTK) and Differential Processing

TUSAGA-Aktif provides real-time corrections via network RTK and DGPS (Differential GPS) techniques, enabling users to achieve centimeter-level positioning accuracy. Two primary criteria are essential for optimal performance: sufficient satellite visibility (minimum five GNSS satellites) and uninterrupted data communication between field receivers and the control center. Interruptions in either can degrade correction quality.

Correction algorithms such as Virtual Reference Station (VRS), FKP, and MAC are implemented to interpolate corrections for user locations based on the surrounding reference stations. These methods enhance precision by accounting for spatial variations in GNSS errors.

Scientific and Applied Uses

Geodetic Monitoring and Crustal Studies

Access to continuous GNSS data enables researchers to monitor crustal movements and tectonic deformation with high resolution. For example, analyses of GNSS measurements from the TUSAGA-Aktif network have been used to assess deformation patterns following significant seismic events in the Aegean region. Such studies demonstrate the system's potential in seismic hazard assessment and earth science research.

Atmospheric Research

Beyond positioning, multi-constellation GNSS data contribute to atmospheric modeling. Tropospheric delay estimates derived from GNSS signals are valuable for meteorological studies and climate research, allowing the integration of GNSS observations into atmospheric inversion models.

Operational Challenges and Considerations

Despite its robust design, the system's performance is inherently linked to satellite geometry and communication reliability. Atmospheric disturbances, signal obstruction, or inadequate network coverage in border regions may limit accuracy. Furthermore, interference such as signal jamming can impede real-time corrections if communication links are disrupted

Future Perspectives

As national infrastructure, TUSAGA-Aktif offers a platform for expanding Turkey's geospatial and scientific capabilities. Enhancements might include integration with multi-GNSS constellations, improved atmospheric modeling, and expanded services for autonomous systems. Future research could also focus on optimizing real-time correction algorithms in regions with sparse reference stations.

TUSAGA-Aktif exemplifies a national commitment to high-precision GNSS infrastructure, bridging foundational geodetic positioning with advanced scientific applications. Its continuous data streams and real-time correction services support engineering, surveying, geoscience, and atmospheric research. As GNSS technologies continue to evolve, systems like TUSAGA-Aktif will remain pivotal for both national development and global scientific collaboration.

Use of GNSS Satellites in Disaster and Emergency Management in Türkiye

Türkiye is located in one of the most seismically active regions of the world and is frequently exposed to various natural hazards such as earthquakes, landslides, floods, and ground deformations. In this context, Global Navigation Satellite Systems (GNSS) play a critical role in disaster risk reduction, emergency response, and post-disaster recovery processes.

Earthquake Monitoring and Crustal Deformation Analysis

One of the most critical applications of GNSS technology in Türkiye is the monitoring of crustal deformation associated with major earthquakes and other geophysical hazards. Located along the Alpine–Himalayan seismic belt, Türkiye is exposed not only to frequent and destructive earthquakes but also to landslides, floods, and ground subsidence events. In this multi-hazard context, continuous GNSS observations provide indispensable spatial and temporal information for both scientific research and disaster management.

In recent years, national GNSS networks such as TUSAGA-Aktif have played a key role in analyzing major seismic events. Following the 2020 Elazığ (Sivrice) earthquake (Mw 6.8), GNSS measurements revealed significant co-seismic and post-seismic displacements along the East Anatolian Fault Zone. These observations enabled detailed assessments of fault slip distribution and post-seismic relaxation processes, contributing to improved seismic hazard modeling in eastern Türkiye.

Similarly, the 2020 İzmir (Aegean Sea) earthquake (Mw 7.0) was investigated using continuous GNSS data to evaluate both onshore and offshore deformation patterns. GNSS-derived displacement vectors supported integrated analyses combining geodetic, seismic, and tsunami-related observations, highlighting the importance of GNSS in coastal hazard assessment.

The most prominent recent example is the 6 February 2023 Kahramanmaraş earthquake sequence (Mw 7.7 and Mw 7.6), one of the largest seismic disasters in Türkiye's modern history. GNSS observations recorded surface displacements reaching several meters along the East Anatolian Fault system. Real-time and post-processed GNSS data were rapidly used to map rupture extents, quantify co-seismic deformation, and monitor post-seismic ground movements. These analyses provided critical input for emergency response, damage assessment, and long-term reassessment of regional seismic risk [10-12].

Beyond earthquakes, GNSS technology has also been widely applied to monitor non-seismic hazards. In landslide-prone regions, particularly along the Black Sea coast and in Eastern Anatolia, continuous GNSS stations have been deployed to detect slow-moving slope instabilities. GNSS-based displacement time series have enabled the identification of acceleration phases preceding landslide events, supporting early warning systems and risk mitigation strategies.

GNSS has further been utilized in the assessment of flood-related ground deformation and subsidence, especially in river basins and low-lying areas affected by prolonged rainfall. High-precision GNSS-derived elevation data have contributed to the monitoring of levees, embankments, and flood protection structures, as well as to post-flood terrain change analyses.

In addition, GNSS observations have been employed to investigate ground subsidence phenomena related to groundwater extraction and urbanization in several metropolitan areas. These measurements are crucial for distinguishing between tectonic deformation and anthropogenic surface movements, particularly in post-disaster urban recovery phases.

In addition to seismic and hydrometeorological hazards, GNSS technology has been increasingly used to monitor sinkhole (collapse doline) formation in the Konya Closed Basin and its surrounding regions, where ground collapses have become a significant geohazard in recent years. These sinkholes are primarily associated with excessive groundwater extraction, karstic geological formations, and subsurface cavity development. Continuous and campaign-based GNSS measurements have been employed to detect subtle surface deformations and gradual subsidence preceding sinkhole formation. GNSS-derived displacement data enable the identification of localized ground instability zones and provide valuable information for assessing sinkhole susceptibility. The integration of GNSS observations with geological and hydrogeological data contributes to early detection efforts, supports land-use planning, and enhances risk mitigation strategies in agricultural and residential areas affected by sinkhole activity.

Overall, the integration of GNSS into multi-hazard monitoring frameworks in Türkiye has significantly enhanced the capability to detect, quantify, and interpret ground deformation processes across a wide range of natural hazards. These applications demonstrate that GNSS is not only a fundamental tool for earthquake science but also a key component of comprehensive disaster risk management and resilience planning.

Post-Disaster Damage Assessment and Infrastructure Monitoring

In the aftermath of disasters, GNSS-based positioning provides rapid and accurate spatial information essential for damage assessment. The precise determination of the locations of collapsed buildings, damaged transportation networks, and critical infrastructure allows emergency management authorities to prioritize response actions effectively.

Additionally, GNSS is employed to monitor structural displacements in bridges, dams, and other critical facilities, helping to identify potential secondary hazards and ensuring the safety of rescue and recovery operations.

Search and Rescue Operations

GNSS technology significantly enhances the efficiency of search and rescue operations by enabling real-time positioning and tracking of response teams and equipment. GNSS-supported navigation systems are widely used by emergency personnel to access affected areas safely and efficiently.

Furthermore, unmanned aerial vehicles (UAVs) equipped with GNSS sensors are increasingly utilized to map disaster zones, identify access routes, and locate survivors. These capabilities improve coordination among response units and reduce operational risks in complex disaster environments.

Landslide and Ground Movement Monitoring

In regions prone to landslides, particularly in the Black Sea and Eastern Anatolia regions, GNSS-based monitoring systems are employed to detect slow ground movements that may precede slope failures. Continuous GNSS stations installed on unstable slopes provide early indicators of acceleration or abnormal motion.

Such observations support early warning mechanisms and contribute to mitigation efforts aimed at reducing casualties and infrastructure losses.

Flood Risk Management and Elevation Control

GNSS-derived elevation data are also utilized in flood risk assessment and hydraulic modeling. Accurate height measurements enable the delineation of flood-prone areas, support the design and monitoring of flood protection structures, and facilitate post-flood terrain change analysis.

These applications are particularly valuable in low-lying coastal areas and river basins where precise vertical accuracy is essential for effective flood management.

Time Synchronization and Emergency Communication

Beyond positioning, GNSS provides precise time synchronization, which is vital for the operation of communication networks during emergencies. Reliable GNSS time signals support the synchronization of telecommunication systems, power grids, and emergency coordination platforms, ensuring continuity of services when conventional infrastructure is disrupted.

Conclusion

The integration of GNSS technologies into disaster and emergency management practices in Türkiye has significantly enhanced the country’s capacity to monitor hazards, respond effectively to emergencies, and support post-disaster recovery efforts. Continuous GNSS observations, real-time positioning services, and time synchronization capabilities collectively contribute to improved situational awareness and decision-making. As GNSS infrastructure and multi-constellation technologies continue to evolve, their role in strengthening national resilience against natural hazards is expected to become even more prominent.

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