論 文 内 容 の 要 旨

This dissertation is about infrasound propagation modeling in the atmosphere from different case studies; natural and man-made infrasound sources, the infrasonic waves can be characterized by the low frequency content which could be transmitted to thousands of kilometers through the refracted rays on the atmosphere. However, there are some limitations for the propagation due to the wind effect on the pressure waves as well as the change of atmospheric parameters with altitudes.
This dissertation is important to understand the nature of infrasound propagation and identifying the different infrasound phases and the exact atmospheric layer which the waves could be refracted from as well as the turning heights of these rays.
In infrasound the array analysis such as Progressive Multi Channel Cross Correlation (PMCC) is commonly used to identify the apparent velocity and the back-azimuth of detected waves through assuming their propagation as a plane wave. In addition, the location estimation for infrasound sources is much complicated, as the cross-bearing method from the estimated back-azimuths is used to locate the infrasound source. However, such these location estimations have uncertainty, as the propagation effect must be taken on account.
In this study, the numerical modeling methods of the infrasound waves were correlated with the real observations from several data sources such as KUT infrasound sensors Network, International Monitoring System (IMS) infrasound stations and volcanoes observatories in Kyushu Island.
The dissertation consists of investigated study on three different sources of infrasound. In the first case study, we focused on all the possibilities for infrasound detection generated from earthquakes using local dense infrasound network, the results proved one additional possibility of coupling from earthquakes through the conversion of seismic waves to acoustics which can be happened through the generating of the T-phase from oceanic earthquakes. Furthermore, the numerical modeling methods (raytracing, normal modes and parabolic equation) confirmed the infrasound arrivals to infrasound sites. In the second case study, two near surface chemical explosions were investigated, as there was a good example for long range propagation of infrasound waves. In addition, the seismo-acoustics signature of such explosions was identified, in this study, the infrasound propagation has an obvious effect on the recorded signals, in addition, the yield in equivalent to TNT of such explosions were estimated from seismic and infrasonic datasets, moreover, the surface damages were detected by InSAR. In order to evaluate the estimated yield charge, the empirical overpressure and damage relation was applied. In the third case study, the infrasound propagation modeling techniques were applied on a movable source (rockets).
KUT sensors network detected four rocket launches of HTV missions, in this study, the attenuation on acoustic energy were modeled at different elevations, to predict the exact altitude where the duct could be happened during the launch in the atmosphere, in addition, near infrasound observatories datasets were used to identify the silent zone. Furthermore, the near and far field recordings are important in rocket induced infrasound detection to identify the different infrasound phases. In addition, the propagation modeling is a key to understand the arrivals at the stations.

In this first case study, Kochi University of Technology (KUT) Infrasound Sensor Network contains 30 infrasound sensors which are distributed all over Japan, a large number of sensors are located in Shikoku Island, all infrasound stations installed with accelerometers to measure the peak ground acceleration (PGA) which can be a good detector for infrasound sources occur on or under the ground

like earthquakes.
Many earthquakes detected by our network after establishing of the network since 2016. In this study we will focus on all the possibilities for infrasound detection from earthquakes using KUT sensor network and International Monitoring system (IMS) stations for the earthquakes which were detected in southern of Japan during 2019.

The selected events for this study are recorded in different international databases; Reviewed Event Bulletin (REB) database of International Data Center (IDC) , Japan Meteorological Agency (JMA) and United States Geological Survey (USGS). There are different scenarios for infrasound coupling from earthquakes one of these scenarios is the conversion of seismic waves to acoustic from the generated T-phases of oceanic earthquakes. On 09 of May 2019, at 23:48:00 UTC an earthquake with magnitude 6.0 mb happened in west of Kyushu Island and infrasound sensors recorded a clear P-waves, However station K53 and I30JP recorded infrasound waves at distances ranges between 850 to 870 km, In addition to T-phases well-recorded from the earthquake in H11N station near Wake island at 3750 km from the event. Progressive multi-channel cross correlation method applied on both infrasound and hydroacoustic data to identify the arrival phases and the back-azimuth of the waves from station to the source.

Moreover, infrasound propagation simulation applied to the event to confirm the infrasound arrivals. Ground to Space Model (AVO-G2S) used with HWM-14 and NRL-MSISE to construct the atmospheric profile for higher altitudes up to 180 km over the event area, furthermore the 3d ray tracing process and the calculation of the transmission loss equation by normal modes and parabolic equation methods applied.

In conclusion this study shows the earthquake detectability from infrasound waves using local infrasound sensors for the largest earthquakes occurred in southern of Japan during 2019. Many parameters control the generation of infrasound from earthquakes; magnitude, depth, mechanism and the topographic features. In addition to the T-phases generation through the SOFAR layer can be an evidence of seismic conversion to sound for the oceanic earthquakes as occurred on the earthquake of 09 May 2019, after applying the propagation simulation with (AVO-G2S) model on this earthquake the tropospheric arrivals confirmed and the calculated celerities well-correlated with the real detected data.

In this second case study, Chemical explosions are ground truth events that provide data which in turn can enhance our understanding of wave propagation, damage assessment and yield estimation. On 4 August 2020, Beirut, Lebanon shocked by a catastrophic explosion that cause devastating damage to the Mediterranean city. Second strong chemical explosion was the Xiangshui, China chemical plant explosion on 21 March 2019. Both events generated shock waves that transitioned to infrasound wave, seismic waves as well as generating hydroacoustic with accompanying T-phases in the case of Beirut event. In this work, we investigate the two events seismo-acoustic signatures, yield and associated damage. DInSAR analysis quantified the surface damage and evaluate the estimated yield-range in equivalent to TNT through "Boom" relation of peak overpressure.

Infrasound propagation modeling identifies a strong duct in the stratosphere with propagation to the west in the case of Beirut-Port explosion. In the case of the Xiangshui explosion, the modeling supports the tropospheric propagation toward Kochi University of Technology (KUT) sensor network in Japan. Although the Beirut yield (202-270 ± 100 tons) is slightly higher than the Xiangshui (201 ± 83.5 tons), near-source damage areas are almost the same based on the distribution of surrounding buildings.

In the third case study, Nowadays, infrasound technology is to be involved in many applications. As the generation of shockwave in different layers in the atmosphere is a key to detect and track

movable objects. Rockets can be considered one of important infrasound sources which emit acoustic signals during the launch process and the re-entry in atmosphere.
H-II Transfer Vehicle KOUNOTORI (HTV) which delivers the supplying to International Space Station (ISS) started the first mission since 2009 and operated annually until 2020 from Tanegashima Space Center. In this study we will focus on the propagation conditions at Tanegashima site and the possible stratospheric ducting to Kochi University of Technology (KUT) Infrasound Sensor Network all of the seasons. Furthermore, KUT sensor Network recorded infrasound signals induced by HTV-06 through HTV-09. In addition, I30-JP infrasound observatory of the international monitoring system (IMS) recorded some phases as well. Because of the complexity of the rocket source, the assumption of point source was applied in this study to identify the approximate height of the source in different stages which are generated infrasonic waves. Infrasound propagation modeling was applied to identify the predicted infrasound phases which could reach to the stations. Ray tracing and normal mode numerical methods were also used to estimate the expected celerities and the transmission loss from the source to stations from different altitudes.

In conclusions, the understanding of infrasound waves depends on the way of coupling in the atmosphere and the propagation path effect, with availability of heigh accurate Numerical Wind Prediction (NWP), In this study several high-resolution data sources of NWP were used in the propagation modeling such as Modern-Era Retrospective analysis for Research and Applications (MERRA-2), National Centers for Environmental Prediction (NCEP), European Centre for Medium-Range Weather Forecasts (ECMWF) and Horizontal Wind Model 14 (HWM14) for higher altitudes. The dissertation focused in natural infrasound source (earthquakes) and two cases of man-made infrasound source (chemical explosions and rocket launches). Besides, understanding the way of infrasound coupling in atmosphere, the infrasound propagation is necessary for identifying the infrasonic phases.
In the first case study, the conversion of T-phase to infrasound was proved and confirmed by several datasets including the hydroacoustic station in Wake Island. In addition, PMCC analysis for both I30JP and H11N detected signals which referred to the site of the epicenter location of the earthquake. Furthermore, the infrasound propagation modeling estimated the rays from the earthquake epicenter location to I30JP and KUT sensors network which confirmed the arrivals from troposphere and thermosphere, however the evaluation of the transmission loss in signal using the parabolic equation modeling didn’t confirm the arrival of thermospheric phase at I30 JP

The propagation modeling can predict the arrivals of infrasound waves with less uncertainty, in addition, the infrasound automatic detection systems could be improved by integration the infrasound propagation modeling in their systems.