Radar Applications to Temporal Change Monitoring of Environment(環境の経年変化モニタリングを目的としたレーダ技術の応用)

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授与学位	博士（学術）
学位記番号	学術（環）博第１０４号
学位授与年月日	平成２１年３月25日
学位授与の根拠法規	学位規則第４条第１項
研究科，専攻の名称	東北大学大学院環境科学研究科（博士課程）環境科学専攻
学位論文題目	Radar Applications to Temporal Change Monitoring of Environment （環境の経年変化モニタリングを目的としたレーダ技術の応用）
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論文内容要旨

This research work aims to develop radar technologies for the monitoring of environmental temporal change. Two radar systems for different monitoring purposes were addressed. The most of the part of thesis from Chapter 2 to 5 are devoted for the development and application of directional borehole radar for underground monitoring. Main emphasis is put on the improvement of the system in terms of high coherent signal acquisition over wide frequency bandwidth. Experimental results demonstrated the ability to detect the subsurface target such as a tunnel and fractures in 3-D manner. Future application of borehole radar for underground monitoring purpose is also proposed. Another radar system addressed in this thesis is Interferometric GB-SAR for long-term monitoring of landslide movement on mountain slope. Interferometric GB-SAR data provided by the TECHLab (Technology for Environmental and Cultural Heritage Laboratory) in University of Florence was analyzed. Followings are the summary of each chapter.

In Chapter 2, a directional borehole radar system design and a DOA estimation method is presented. A circular array consisting of four dipole antennas evenly spaced on a circumference is used as a receiver. Feeding point of the each dipole antenna is terminated by an optical electric field sensor which enables a measurement without interference with metallic cables and devices as in the case of other borehole radar system. Therefore, highly accurate phase information is obtainable. A DOA method presented in this chapter is based on the Adcock antenna principle. Differentiation of receiving voltages of two closely located dipole antennas produce an equivalent loop antenna radiation pattern. Two mutually orthogonal loop antennas are linearly combined to get a loop oriented to arbitrary direction. 180 degree ambiguity of the loop antenna is resolved by comparing the phase of the loop antenna with that of a dipole antenna. All the expression of a time trace in this chapter is represented in complex number called analytic signal as it simplifies the calculation above. The advantage of this method is that the radiation pattern of the loop antenna is narrowest among those antennas which fit into a small borehole space. Another advantage of this method is that it can be combined with the image processing methods such as the migration and the f-k domain filtering without the distortion of the phase information as it is demonstrated in Chapter 3. One thing which was not explicitly described is that the optimization algorithm proposed in this chapter is only effective when S/N of array elements are unbalanced. It can be mathematically proven that when

all the array elements have the same S/N, the algorithm offers no improvement of S/N. But generally at least few dB gain unbalance is produced due to manufacturing error of optical electric field sensors and electric devices.

Chapter 3 describes a field test of the directional borehole radar system and the DOA algorithm proposed in Chapter 2 is applied. As a preliminary test, a cross-hole fan measurement was conducted and successfully detected a correct direction of arrival of direct wave. A single-hole measurement was also conducted in order to locate a subsurface tunnel whose exact location is already known from the past surveys. A hyperbolic reflection pattern from a tunnel was clearly recorded in a dipole profile, but the loop antenna profile suffer from noise due to low antenna gain. In addition, the reflection signal from the tunnel is partially obscured by clutters. Therefore, the azimuth detection of the tunnel was not accurately done. Correct azimuth location of the tunnel was successfully detected as a result of the reduction of clutters and improvement of S/N by moving averaging subtraction and the migration processing.

Chapter 4 describes an issue of mutual coupling among the receiving array elements which was not explicitly addressed in the preceding chapters. It was obvious from the measurement dataset that the low frequency part of the measured data acquired by four array elements are highly correlated each other but abrupt change of the spectrum and phase at higher frequency causes the ringing in time trace and render the signals less coherent. Since the DOA algorithm proposed in Chapter 2 does not assume such interference among the array elements, there were no means to remove the mutual coupling effect other than rejecting the higher frequency components by a frequency low pass filter. But it accompanies the deterioration of S/N and range resolution due to frequency band limit. Laboratory experiment revealed a presence of mutual coupling which is most prominently observed at a resonant frequency of antenna. To reduce the mutual coupling and to utilize wider frequency bandwidth, a PIN diode switching circuit was placed on each antenna elements for the electrical control of dual resonant frequency. By making the resonant frequency of three parasitic dipole elements higher than the rest of dipole with which data is acquired, a frequency of the mutual coupling outbreak is raised to a resonant frequency of parasitic dipoles. As a result the high correlation among signals acquired by the array dipole elements is obtained at wider frequency bandwidth. A laboratory experiment and a field experiment demonstrated 30% increase of bandwidth in air and 25% increase in water-filled borehole, respectively, by the switching operation.

Chapter 5 addresses an issue how to apply the borehole radar for underground monitoring purpose. One of the most important applications of borehole radar is the assessment of underground hydrogeological condition which will be necessary in the site selection of underground nuclear disposal and underground oil storage. Detection of 3-D geometrical structure of fractures by directional borehole radar is attempted in the first part of this chapter using a single-hole data in Kamaishi mine. The result shows (see Fig.1) good reliability of the estimated azimuth location of fractures as individual fractures show consistent azimuth direction along the depth and high repeatability of the result was confirmed. The latter part of this chapter discusses the future application of borehole radar for the long-term monitoring of underground temporal change which especially will be important for the monitoring of nuclear waste disposal site. A feasibility analysis on requirements necessary for the long-term monitoring of small temporal change on the order of 1mm/year of subsurface target by borehole radar is presented. Acceptable tolerance of the stability of measurement equipments and variation of transmission line length due to the thermal expansion of optical fibers are examined. Crucial problems are the variation of time delay through long optical fiber due to temperature change and also relatively large time instability of optical/electric devices. A radar system with auto calibration function is proposed. In addition, antennas must be implanted in a borehole to detect a small change in reflected signal, therefore, remote power supply system is essential. Most promising way is to use a photovoltaic power converter at a transmitting point to supply electric power to the optical/electric converter device. Integration of all these technologies is necessary to realize the semipermanent underground monitoring.

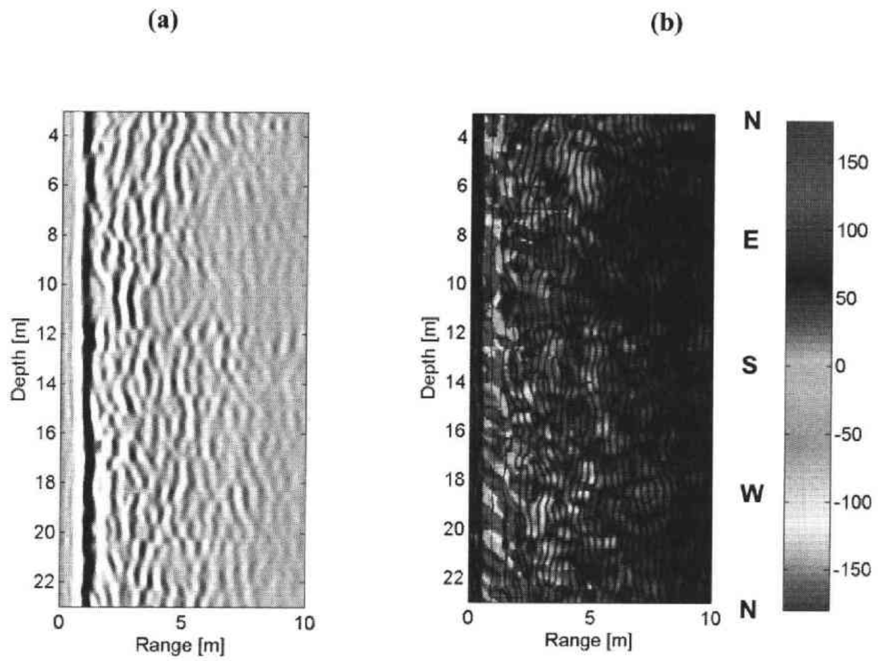

Fig1 Result of a single-hole radar measurement in Kamaishi Mine (a) Reflection profile. Reflection patterns are fractures surrounding a borehole. (b)Color representation of azimuth direction of fractures

Chapter 6 addresses an analysis of Interferometric GB-SAR data obtained periodically over 3 years with an attempt to detect the landslide displacement of landslide which has a velocity of a few centimetres per year. Although the processing scheme is similar to those presented in satellite differential interferometric SAR, several points were modified in order to make the best use of the data which is peculiar to our interferometric GB-SAR observation. 15 interferograms are generated by pairing 6 SAR images. Coherent scatteres (CSs) were first identified by examining amplitude variation of SAR images available in each measurement campaign. Pixels showing small amplitude variation in all the measurement campaigns were identified as CS. Then, rough estimation of velocity was carried out using a spectrum analysis based on a phase model which is a function of LOS target velocity and linear spatial atmospheric phase screen. This rough estimation of velocity is used to get a first estimate of phase difference between the adjacent pixels in the 2-D phase unwrapping, otherwise, phase cycle lost is produced at some area. After the phase unwrapping, temporal consistency of the wrapped interferograms is checked, and pixels showing temporal inconsistency is excluded from CS. According to the first rough estimate of velocity, CSs showing a small velocity is extracted and linear spatial atmospheric screen is estimated based on those points. If all the CSs are examined for the estimation of the atmospheric phase screen, phase of some pixels containing a large motion component could cause a large atmospheric offset error. Then after, LOS displacements of CSs are solved in a least square sense. The result of the displacement map successfully highlighted an area affected by the landslide as shown in Fig.2.

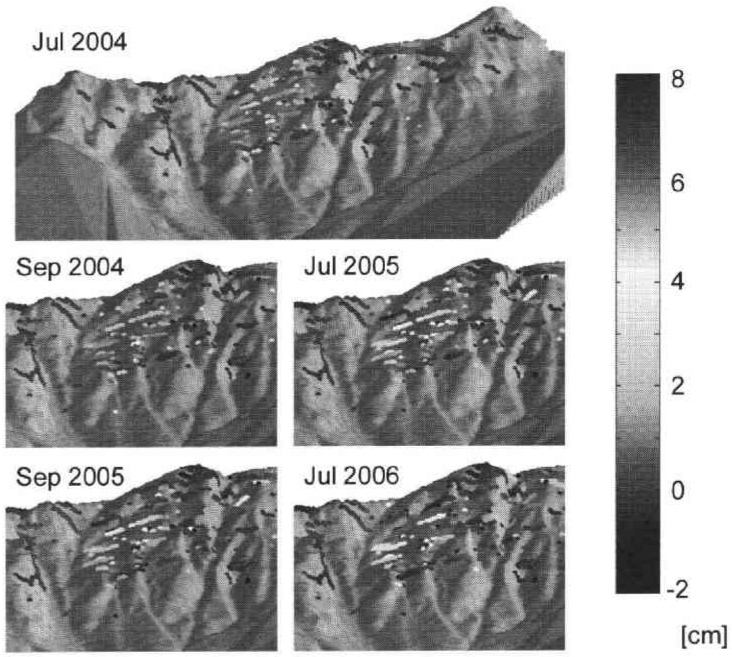

Fig.6.13 LOS displacements with respect to the first survey.

Eestablishment of directional borehole radar system and its successful result on the detection of 3-D location of tunnel and 3-D geometrical structure of fractures, future underground monitoring methodology by borehole radar, and the successful application of GB-SAR for landslide monitoring have great social impact. Directional borehole radar has vast future applications e.g., estimation of water permeability of rock for the site selection of underground nuclear disposal and oil storage, efficient geo-thermal power generation, prevention of rock slide accident during the tunnelling, stress field analysis of bedrock for seismological application. Conventional non-directional borehole radar system can be replaced with the directional without any burden to users because the completely the same setup and data acquisition procedure are necessary. Interferometric radar techniques are already extensively studied enough in the field of satellite SAR remote sensing and now it is used frequently for the purpose of disaster monitoring and prevention. Ground-based SAR system discussed in this thesis uses an exactly the same principle as the satellite mounted SAR has many practical advantages e.g., high mobility of the system and accessibility to any location, high data sampling rate for short term and fast moving target monitoring as well as long term monitoring application, flexible parameter choice of frequency and range. Successful result in chapter 6 suggests potential use of GB-SAR as a site specific monitoring tool. A quick alarm system for evacuation based on full time monitoring of volcanic activity and landslide by GB-SAR is one of the highly expected applications for the disaster prevention.

論文審査結果の要旨

気象レーダ、衛星レーダリモートセンシングなど、災害の防止、予測を目的とした様々なレーダ計測が現在、定常的に行われている。本論文はレーダによる環境の経年変化測定を目的とした新たな応用に関し、主に二つのレーダシステムを用いた環境計測について論じている。

一つ目はボアホールレーダによる地下計測である。近年話題となっている高レベルの核廃棄物地層処分、石油地下備蓄など地下利用においてはサイト選定、また継続的なモニタリング技術の確立が必要となる。地下の詳細な情報を得るために開発を行った指向性ボアホールレーダは、受信アンテナに4つのダイポールアンテナを周方向に配置したアレーアンテナを用いることにより三次元的な地下ターゲットの位置推定を行うシステムである。本システムの大きな特徴として、光電界センサを受信アンテナとして用いることにより非常に高精度な信号検出が可能となることである。また到来方向推定アルゴリズムの提案、受信アンテナ間の相互結合による信号のコヒーレンスの低下を防ぐために共振周波数可変型のダイポールアンテナを提案を行い、より高精度に三次元位置検出を行う手法を確立した。フィールド実験での検証の結果、既知の地下トンネルの三次元位置を小さな誤差において推定可能であることを示した。また地下き裂の位置推定を行い、個々のき裂の三次元構造の推定が可能であることを確認した。これは地下の透水性を評価する上で重要な情報となり、今後の応用が大いに期待される。また将来必要となる地下モニタリング手法として、非常に小さな変化を長期間にわたって計測するためのボアホールレーダシステムの提案を行った。

本論文の二つ目の議題として、インターフェロメトリを利用した地表設置型合成開口レーダ（GB-SAR)による地表変動の長期モニタリング解析を行った。この技術は衛星リモートセンシングにおいて盛んに行われているもののGB-SARにおいて長期観測を行った例はまだない。またGB-SARは計測時間、場所において自由度が高く、特定地域の集中的な火山活動、地滑りの観測に今後の応用が期待されている。今回3年にわたって継続的に計測したデータを用いインターフェロメトリ解析を行い、最大で3cm/year程度の微小変化を受けている領域の特定に成功した。本技術は火山活動、地すべり観測による災害時の緊急避難警報システムなどに応用が期待される。

本論文はレーダを環境計測に利用する場合の可能性を広い視野に立ち、新しい領域を果敢に開拓する優れた知見を得て、それについて詳しく論じた。特に、長期間にわたる微小な変位や変化などを高精度に計測する技術を明らかにした点でその成果は高く評価できる。

よって，本論文は博士(学術)の学位論文として合格と認める。