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論文要旨

Complex dynamical systems, we see in the world around us, are emergent, self-organized and interesting in structures. Examples of complex systems include quasar systems, human economies, nervous systems, as well as human beings and their psychology, emotions, bodies and interactions etc. Complex systems may exhibit relatively simple patterns of behavior just as simple as linear systems. However, unlike linear systems, complex non-linear systems are usually unpredictable in terms of exhibiting different behaviors at different times, and it is hard to understand the process of the emergence and self-organization.

However, time series analysis seems to be one of the useful methods, which makes possible to access mechanisms of the process. The time series is a sequences of numerical data derived from a system, which is measured in course of time. Mathematically, a time series describes the state of a data with the value of x_t at time sequence t,

$$\{x_t\}_{t=1}^{N}$$

The time series is an enormous field of study in mathematical statistics, econometrics, astronomy, signal processing and many other fields of complex systems.

Generally, linear methods are used for time series analysis. However, complex systems are antithetical and refuse the linear methods to solve. The nonlinear method, which has been developed recent years, has useful instruments to cut into time series data and provide meaningful information about the emergence and self-organization.

The thesis represents an approach of time series analysis which is based on the theory of nonlinear dynamics in an attempt to access information about the emergence and self-organization of the complex systems. Moreover, noise may superimpose on observed time series, which may lead to an erroneous result. Effects of the noise on the time series were estimated. On the other hand, missing data is unavoidably included in daily observed time series. The way of processing regularly and irregularly missing data was also discussed.

The paper starts from an outline of underlying analysis methods. The methods were illustrated using a large number of empirical data sets taken from various fields, like, radio astronomy, econometrics and human brain wave. Deterministic models' time series with known random noise was considered and the methods were applied to estimate the noise level, Hurst exponent, fractal dimension and correlation dimension of the dynamics, simultaneously.

The paper contains seven chapters including an introductory chapter and conclusion; and in Appendix computer programs written in Mathematica.

Chapter 2 presents a brief overview of some methods and tools that are used in my research. In the first step, I used fractal dimension and Hurst exponents for data analysis. In the second step, correlation sum analysis was used.

Chapter 3 depicts an attempt to find informational structure expressing the evolution and self-organization of extra-galactic systems at cosmological distances. In this chapter, the time series of variable intensity of the radio wave from 28 quasars, whose red shift ranges from 0.158 to 2.225, were analyzed using the methods of fractal dimension, Hurst exponent and correlation sum of reconstructed time series. The distances of the quasar are from a few billion to more than ten billion light years.

Fractal dimension and Hurst exponent of the radio wave intensity time series were calculated by Higuchi's fractal dimension method and Hurst's rescaled range analysis method, respectively. The relationship between the red shift, which represents the cosmological distance of the quasar and is denoted by z, and the fractal dimension of the quasar showed a dependence in the region $z \lesssim 1$. The correlation sum based on G-P method suggested that expected dimension of the dynamical system may be limited.

Chapter 4 discusses an estimation of superimposed noise on the radio wave intensity time series using correlation sum. The intensity of the radio wave that was emitted by synchrotron radiation from the quasar and observed on the earth may be contaminated with noise because of the external effects on the path of wave propagation. To estimate the superimposed noise, the correlation dimension of the reconstructed time series was calculated for the 28 quasars and plotted versus the red shift of the quasar. A dependence was found between the red shift and the correlation dimension. This may proof that external noise may be superimposed on the original radio wave intensity during the wave propagation.

A convolution method was applied on the original time series to filter noise, and the processed time series were analyzed using the correlation sum. Less dependence was found between the red shift and the correlation dimension for the processed time series, which may show a major dynamics of the intensity variations.

Chapter 5 depicts the estimation of effects of missing data in the time series. Missing data, or absence of data, can not be avoided in daily observation because of holidays or a sudden breakdown of the observational system. The missing data may lead to an erroneous result of data analysis. To get rid of the wrong result, the effect of the missing data in economic and astronomical time series were estimated using the correlation sum analysis. A model estimation was given for the Lorenz time series.

A compensation method, which is used to compensate missing data by an average of its neighbors, is effective for the time series with irregularly missing data. An elimination method, which is used to eliminate vectors containing the missing component from the reconstructed time series, is effective for processing regularly missing data when the time lag is a multiple of the duration of missing.

In order to seek a mathematical model of the human brain activity, the brain magnetic wave was measured with the magnetoencephalography (MEG) of healthy subjects and the time series data was analyzed in Chapter 6. The MEG raw data were recorded at 122 channels at the sampling frequency of 400 Hz with a band pass of 0.03 to 100 Hz. The reconstructed time series of brain alpha wave, which was measured over the occipital brain cortex, was calculated with the G-P method. The correlation dimension of the alpha wave is around 4 with the G-P method and the dimension is assured by the analysis with the Judd method for the healthy subject. The detailed and systematic alpha wave analysis extending to a lot of subjects may be expected to make a database for brain diagnosis.

審査結果の要旨

この学位論文の目的は，実世界の動力学システム(Dynamical System)から発生した時系列データを非線形時系列解析分野の数理的手法を用いて解析し，システムの動力学的な数理的構造を明らかにすることである．

カオスの数理解析理論の中で特に重要と位置づけられている Takens の「埋め込み定理」に立脚して開発された手法である，相関次元等の非線形時系列解析手法を用い，(i)本質的に予測不可能な，宇宙論的な距離にあるクェーサーの電波強度(物理システム)，(ii)大脳皮質で発生する脳磁アルファ波(生体システム)及び(iii)為替レート(経済システム) の動力学システムで発生する時系列データを解析している．

電波強度の時系列解析では，フラクタル次元とハースト指数を解析した結果，クェーサーは宇宙論的距離の変化により異なった変動構造を有すること，また，埋め込み定理に基づき，時系列生成力学系における多様体の相関次元が限定された次元であることを示している．次に，雑音重畳を仮定し，雑音除去操作後に行った解析では，距離にかかわらずシステムの相関次元が 2 程度と非常に低い値になるという結果を得ている．これは，雑音除去による時系列に含まれる小振幅情報消失の可能性も無視できないが，クェーサーの時系列生成力学系における固有の性質を示唆する結果である．脳磁アルファ波の時系列解析では，その相関次元が 3 から 4 の間の低次元システムであることを示し，アルファ波の伝播と相関次元の空間分布との関連を考察している．

観測時系列データは，通常完全には揃っておらず，ランダムまたは周期的な欠落がある．この論文では，欠落データに対する補完法のアルゴリズムを導き，電波強度時系列および為替レート時系列の相関次元に及ぼす誤差を評価し，周期的欠落の時系列に対しては再構成ベクトルを生成する最適条件を導いている．この結果は，従来の線形補完法では大きな誤差を生じる，周期的欠落をもつ経済数値時系列等の相関次元解析に適用可能である．

以上の通り，この論文では従来の線形解析手法では扱えなかった複雑システムの時系列データに様々な非線形解析手法を適用し，システムが有する動力学的な数理構造を明らかにしており，今後の新しい展開が大いに期待できる．学位論文審査委員会は，学位論文の審査ならびに最終試験の結果から，申請者に対して博士(理学)の学位を授与することを適当と認める．