Astronomy and Computing 14 (2016) 43–51

Contents lists available at ScienceDirect

Astronomy and Computing

journal homepage: www.elsevier.com/locate/ascom

Full length article

Dynamic process analysis by moments of extreme orders

S. Šimberová[a,*], T. Suk[b]

[a] Astronomical Institute, The Czech Academy of Sciences, 251 65 Ondřejov, Czech Republic

[b] Institute of Information Theory and Automation, The Czech Academy of Sciences, 182 08 Prague 8, Czech Republic

ARTICLE INFO

Article history:
Received 3 December 2014
Accepted 9 January 2016
Available online 18 January 2016

Keywords:
High-order moments
Principal component analysis
Frequency analysis
Solar flares

ABSTRACT

Dynamic processes in astronomical observations are captured in various video sequences. The image datacubes are represented by the datasets of random variables. Diagnostics of a fast developing event is based on the specific behavior of the high-order moments (HOM) in time. The moment curves computed in an image video sequence give valuable information about various phases of the phenomenon and significant periods in the frequency analysis. The proposed method uses statistical moments of high and very high orders to describe and investigate the dynamic process in progress. Since these moments are highly correlated, the method of principal component analysis (PCA) has been suggested for following frequency analysis. PCA can be used both for decorrelation of the moments and for determination of the number of used moments. We experimentally illustrate performance of the method on simulated data. A typical development of the dynamic phenomenon is modeled by the moment time curve. Then applications to the real data sequences follow: solar active regions observed in the spectral line Hα (wavelength 6563 Å—Ondřejov and Kanzelhöhe observatories) in two different angular resolutions. The frequency analysis of the first few principal components showed common periods or quasi-periods of all examined events and the periods specific for individual events. The detailed analysis of the moment's methodology can contribute to the observational mode settings. The method can be applied to video sequences obtained by observing systems with various angular resolutions. It is robust to noise and it can work with high range of sampling frequencies.

1. Introduction

Many natural-science branches solve a common problem with the processing of a video sequence to get valuable information about the records. The ground-based and satellite astronomical observations incorporate video sequences showing various types of events: from stable scene up to the highly dynamic process. The current methods of processing strongly depend not only on the kind of data but also on the ongoing events in video sequences. The image data (2D, 3D, etc.) are represented by the datasets of random variables and from these modeled and/or observed datacubes information is obtained about the events in progress. The dynamic process in astronomy can appear in different kinds of observations, e.g. records of meteoric swarms, flashes of gamma lighting [in seconds], solar flares and prominences [in minutes], etc.

To perform a valuable diagnostics of an event we have chosen statistical moments. Moments are widely used in statistical analysis. Generally they give information about the distribution of data on various platforms. For practical use of moments in statistics, see e.g. Dudewicz and Mishra (1988).

If we choose the moment as a characteristic, then we still have a few options; we can consider the image itself to be a realization of a random field and compute two-dimensional moments from them. This approach is often used in the field of signal processing, image analysis and pattern recognition, see Flusser et al. (2009). Another option is to consider the image histogram as an estimate of a probability density function. In this paper we have chosen the latter one; we are interested in signal evolution in time and this option enables a suitable way how to suppress the spatial information. We still need to select the optimal order of the moments.

Starting with basic statistical moments: the mean value $m_1 = EX$ (first moment), the variance $m_2 = E(X-EX)^2$ (second moment) and its square root $S = \sqrt{E(X-EX)^2}$ (standard deviation), we are approaching the high-order moments—skewness (third moment), and kurtosis (fourth moment). The moments $m_1, \ldots, m_4$

* Corresponding author.
E-mail addresses: ssimbero@asu.cas.cz (S. Šimberová), suk@utia.cas.cz (T. Suk).

http://dx.doi.org/10.1016/j.ascom.2016.01.003

were used e.g. in Leka and Barnes (2003a,b) to analyze physical parameters in active solar regions, the generalized spectral-kurtosis estimator and its statistics is in Nita and Gary (2010a,b). Aharonian et al. (2009) observed oscillations of a specific γ-ray source in the Galactic Center region. They analyzed them by the statistical moment-based Hillas technique (Hillas, 1985) based on the characteristic ellipse, i.e. second-order moments. Rimoldini (2014) proposed unbiased estimators of the weighted skewness and kurtosis moments, corrected for biases due to sample size and Gaussian noise.

The dynamic phenomena in astronomical image processing have been studied in various wavelengths. These events are often observed and described by the means of a light curve, i.e. the brightness of a specific pixel (or average brightness of some region) as a function of time. In context of moments, the light curve equals the first moment m_1. The light curves in Hα were introduced in Švestka and Simon (1969), but it was found they do not describe the event with sufficient accuracy.

Recently, Salakhutdinova and Golovko (2004) observed so called structure functions that enable deeper insight into the physical phenomena in the Sun, but do not express the fine details of the events. Nuño et al. (2008) observed fast events and magnetoacoustic waves, Jackiewicz and Balasubramaniam (2013) deal with regions both with flares and with oscillating filaments and Jardins and Canfield (2003) observed preflare phenomenon called moving blueshift events. All of them used Hα band, the last one in combination with a spectrograph and X-ray band.

Li et al. (2005) were interested in one specific event (2002 July 15) in various bands: optical continuum, Hα, UV continuum, microwave, soft X-rays and high-cadence longitudinal magnetograms. While the previous events are studied in the chromosphere, De Moortel et al. (2002a,b) observed oscillations in the corona, X-ray band. They found that loops situated above the sunspot umbras show oscillations close to 3 min, whereas non-sunspot loops (above plage regions) show oscillations close to 5 min. The flare-generated oscillations from the photosphere to the corona are described in detail in De Pontieu et al. (2005). Quasi-periodic pulsations are studied in Nakariakov and King (2007), Nakariakov and Inglis (2009), Nakariakov et al. (2010). King et al. (2003) observed quasi-periodic disturbances in extreme-ultraviolet band (171 Å and 195 Å) with two ranges of periods: 2–3 min and 5–8 min. A detailed list of relevant references can be found in Wang (2011). Data analysis has been based on the light curves in the above-mentioned cases, while our approach is based on the 3rd and higher moments.

Characteristics of the moments in the active regions during solar flares were studied in Šimberová et al. (2014) and Šimberová and Suk (2013). We found that the last two mentioned moments, skewness and kurtosis, play an important role in the study of this dynamic process. The unusual behavior of both moments was observed by chance while studying development in various areas on the solar disk in Hα images. While the first moment (the light curve) and the second moment do not provide any relevant information about the investigated area in time, the skewness and kurtosis quite clearly and unambiguously identify a "turning point" in the observed dynamical event even with the accuracy to one image plane. This turning point enables to determine the trigger area of the flare, which is important for further image analysis. Now we are able to specify the time sequence of the pre-flare phase and to study physical conditions (magnetic field distribution, density fluctuations, etc.) leading to the flare arising.

To automate the process of determining the start, it is necessary to develop a special algorithm. Searching for the trigger area leads to the turning point (i.e. the start of the increase) on a curve of skewness with respect to time. The turning point can generally be detected as maximum of second derivative. The skewness is (or could be) noisy and we do not want to detect each local maximum of the noise. Therefore, we have designed a special filter combining Gaussian smoothing with the second derivative in Šimberová et al. (2014). An automatic search for local maxima allows the division of a dynamic event into time slots, in which we want to separately perform further analysis, e.g. the time slot up to the turning point enables detailed pre-flare analysis. Of course, we can analyze the behavior of moments throughout the period of observation of the dynamic phenomenon.

In this paper we are going to study, what moment or combination of moments is optimal for image analysis. We suppose the same methodology can be applied to other dynamically developed phenomena in video sequences.

Our article is organized as follows: The next section covers the introduction of statistical high-order moments and principal components in image analysis, the 3rd section involves experiments with real datasets and frequency analysis. Summary and results are discussed in Conclusion.

2. The high-order moments and principal components in image analysis

2.1. The statistical hypermoments

The high-order moments skewness m_3 and kurtosis m_4 are in established notation

$$m_3 = E(X - EX)^3/S^3, \qquad m_4 = E(X - EX)^4/S^4, \tag{1}$$

where EX is the mean value of random variable, S is standard deviation and S^2 is variance. Continuing for $n > 4$

$$m_n = E(X - EX)^n/S^n. \tag{2}$$

The moment m_5 is sometimes called hyperskewness and m_6 hyperflatness.

On the other hand, there is also the zeroth-order moment m_0, called moment about origin. In our case it equals the area of the histogram and the area of the observed region in pixels as well.

Increasing the order of moments it describes more and more details of the histogram. Theoretically, in the case of a continuous function, we can continue up to infinity. In the case of digital image (discrete function), we have some finite L levels of brightness (typically 2^7, or $2^8, 2^9$, etc.), i.e. L bins of the histogram. The moments $m_0, m_1, m_2, m_3, m_4, \ldots, m_{L-1}$ give complete description of the histogram. It also means that there are methods reconstructing the discrete function from the moments.

In practice, the finest details are just noise and the numerical precision also decreases with the moment order. Therefore it is useful to determine a maximum moment order s (much lower than L) in a specific application. We use the limit $s = 10$ in this paper, it has emerged from our experiments with reconstruction from moments— (Flusser et al., 2009), Section 6.5.

The time curves of the high-order moments are also highly correlated. This can be solved either in advance, by use of some type of orthogonal moments, or subsequently, by principal component analysis. Due to the difficulty and risk of the statistical interpretation of orthogonal moments we decided for the latter approach. The time curves of m_3, m_4, m_7 and m_{10} can be compared in Fig. 1. It can be seen that the adjacent moments are highly correlated, nonetheless, they bring new information.