Full-Disk Cloud Contamination Real-Time Detection and Correction System (Post-print)

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Date: 2017-10-20T00:00:00+00:00

Abstract

High-altitude clouds introduce a layer of cloud contamination onto observed H full-disk solar images, obscuring the details of solar activities. To enable real-time detection of cloud contamination and prompt display of restored images, a GPU-based real-time identification and restoration system for H full-disk solar cloud contamination was developed. The system primarily leverages GPU parallelization within the Compute Unified Device Architecture (CUDA) environment to implement: (1) identification of severely cloud-contaminated images via the ellipse major-to-minor axis ratio method on binarized images; (2) identification of restorable cloud-contaminated images through the center symmetry method of the limb-darkening curve; and (3) removal of cloud contamination using frequency-domain Butterworth low-pass filtering. Detailed timing measurements of each operation on the GPU revealed that forward and inverse Fourier transforms together with frequency-domain filtering consume 52.9% of the total GPU processing time, constituting the most computationally intensive portion of the system. Nevertheless, relative to the 1-minute observation interval, the total processing time of approximately 0.7 seconds satisfies the requirements for real-time display. Furthermore, quality assessment of the restored images confirmed that the adopted restoration algorithm effectively removes cloud contamination while minimally affecting solar activity details. Finally, the limitations of the system and required improvements are discussed.

Full Text

Real-Time Detection and Restoration System for Cloud Shadows on Full-Disk Solar Images

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Abstract

High-altitude clouds cause observed H full-disk solar images to be covered with cloud shadows, obscuring the details of solar activities. To enable real-time detection of cloud pollution and timely display of restored images, we have implemented a real-time full-disk cloud shadow detection and restoration system using Graphics Processing Unit (GPU) technology under the Compute Unified Device Architecture (CUDA) environment. The system employs three main approaches: (1) identification of heavily cloud-covered images using the ellipse major-to-minor axis ratio method on binary images; (2) recognition of recoverable cloud-covered images using the central symmetry method of limb-darkening curves; and (3) removal of cloud shadows using frequency-domain Butterworth low-pass filtering. By measuring the processing time of each operation on the GPU in detail, we find that Fourier transforms and frequency-domain filtering account for 52.9% of the total GPU processing time. However, with a total processing time of approximately 0.7 seconds, the system meets the requirements for real-time display. Additionally, through quality evaluation of the restored images, we verify that the restoration algorithm can effectively remove cloud shadows while having minimal impact on solar activity details. Finally, we discuss the system' s limitations and necessary improvements.

Keywords: cloud shadows; parallel computing; detection and restoration; Butterworth low-pass filtering

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1. Introduction

Full-disk solar observations provide extensive data for monitoring chromospheric activity phenomena. Numerous full-disk observation sites exist worldwide, such as the Global Oscillation Network Group (GONG) and various observatories. Although these sites undergo rigorous selection, actual observations frequently encounter cloudy conditions, resulting in partial solar coverage and blurred image details. Cloud coverage represents one type of distortion in full-disk images. Previous researchers have proposed various quality assessment and restoration algorithms for full-disk images, including dual-scale filtering for intensity normalization, kurtosis-based quality assessment using limb-darkening curves, minimum correlation coefficient methods for cloud detection, median filtering for distortion correction, and multi-scale morphological filtering for cloud removal. These methods primarily aim to facilitate subsequent solar physics research by enabling better segmentation and measurement of solar features, but they do not address execution efficiency or processing speed.

If these methods could be adapted for real-time cloud pollution detection and display of restored images, it would significantly benefit observation operations and quality assessment. However, this requires optimized algorithms and high-speed computational capabilities. Therefore, based on previous work, we have implemented a real-time full-disk cloud pollution detection and restoration system using GPU technology. In our hardware environment, the total time to process a cloud-contaminated image is approximately 0.7 seconds, which satisfies the real-time display requirements for observations with 1-minute intervals between images. Using image similarity algorithms, we also perform local similarity verification between clean images and restored cloud-contaminated images. The frequency-domain Butterworth filtering algorithm preserves solar activity details to a large extent while meeting real-time processing needs.

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2. Algorithm Principle Analysis

The processing of cloud-contaminated images involves two steps: cloud detection and cloud removal. Detection includes: (1) determining whether the full-disk image is circular, otherwise classifying it as heavily cloud-contaminated and abandoning restoration; (2) determining whether the limb-darkening curve is centrally symmetric to identify recoverable cloud pollution. Cloud removal employs the template method proposed in previous work, comparing with a standard full-disk template and obtaining cloud transmittance through filtering to restore contaminated images.

2.1 Heavy Cloud Contamination Detection Under normal conditions, the intensity values of the solar disk and sky background in full-disk images differ significantly. A threshold above the sky background can be used for binarization. When cloud contamination is severe, the solar disk appears incomplete in the binary image. By assuming the binary image forms an ellipse and calculating the ratio of its major to minor axes (E), we can determine if the image is incomplete. Statistical analysis of well-observed images shows $E = 1.0010 \pm 0.0015$. In the actual system, images with $E > 1.938$ are classified as heavily contaminated.

2.2 Recoverable Cloud Contamination Detection For images that remain circular after binarization, most have no clouds. The presence of cloud pollution can be determined by checking whether the limb-darkening curve is centrally symmetric. The process involves: (1) centering the solar image and converting it from Cartesian to polar coordinates; (2) obtaining median limb-darkening curves from 12 equal divisions of the polar coordinate image; (3) calculating pairwise correlation coefficients among the 12 curves to find the minimum correlation coefficient. If no cloud pollution exists, this coefficient approaches 1, reflecting the circular symmetry of the limb-darkening curve. The system uses a threshold of 0.95. For example, Figure 1(a) yields a minimum correlation coefficient of 0.99, indicating no cloud pollution, while Figure 1(b) yields 0.32, indicating recoverable cloud pollution.

2.3 Cloud Shadow Removal The imaging model for cloud-contaminated full-disk images can be simplified as:

$$I_{\text{observed}} = I_{\text{clean}} \cdot t$$

where t represents cloud transmittance. The restoration principle can be expressed as:

$$I_{\text{clean}} = \frac{I_{\text{observed}}}{t}$$

The restoration steps are: (1) Process a clean image to obtain its standard limb-darkening profile; (2) Divide the cloud-contaminated image by the standard limb-darkening profile to obtain cloud transmittance containing solar activity details; (3) Convert to frequency domain and apply a Butterworth low-pass filter to remove high-frequency components (solar activity details) and obtain clean cloud transmittance; (4) Divide the original cloud-contaminated image by the cloud transmittance to obtain the final restored image.

Solar activity details in the frequency domain are primarily distributed in the high-frequency region outside a radius D from the center. Therefore, selecting an appropriate radius D in the Butterworth filter can yield cloud transmittance with solar activity details removed. After statistical analysis of cloud-contaminated images from different periods, the cutoff frequency is set to 0.003 of the image size.

2.4 Algorithm Verification To verify restoration reliability, we use the Structural Similarity Index Measurement (SSIM). Two images taken one minute apart are selected: one clean and one cloud-contaminated. The SSIM between the clean image [FIGURE:5(a)] and the cloud-contaminated image [FIGURE:5(b)] is 0.2997, while the SSIM between the clean image and the restored image [FIGURE:5(c)] is 0.7558. The significantly higher structural similarity after restoration demonstrates that frequency-domain filtering effectively removes clouds while preserving solar activity details.

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3. GPU Implementation of Cloud Detection and Restoration

GPUs were originally designed to offload graphics processing from CPUs. Due to their Single Instruction Multiple Data (SIMD) architecture, GPUs possess strong parallel computing capabilities. NVIDIA' s CUDA programming model enables general-purpose computing on GPUs. Full-disk cloud detection and restoration algorithms, characterized by high computational density and strong parallelism, are well-suited for GPU implementation.

The system utilizes existing CUDA libraries: CUFFT for Fourier transforms and CUBLAS for matrix operations, significantly improving efficiency. The CPU handles reading image data from disk, copying data between CPU and GPU memory, and displaying results. The GPU executes the core computational tasks, which are divided into two categories: (1) direct library function calls, and (2) custom parallel functions.

The custom kernel design follows these principles: (1) Allocate total threads based on the number of matrix elements, mapping each point to a thread via thread indexing; (2) Classify computation tasks for each thread based on conditions; (3) Execute all threads in parallel with identical tasks under the same conditions.

Heavy Cloud Detection: Parallel binarization is implemented first, followed by parallel calculation of the ellipse centroid position. The covariance between each ellipse point and the centroid is computed in parallel, and the resulting covariance elements are substituted into formulas to obtain the major-to-minor axis ratio.

Recoverable Cloud Detection: The image is first parallel-centered by translating the solar disk to the image center. Parallel bilinear interpolation then converts the image to polar coordinates. The polar coordinate image is divided into 12 equal angular regions, each sorted using a parallel bitonic sorting algorithm. The required 12 limb-darkening curves are extracted from the sorted polar image. Correlation coefficients between curve pairs are calculated using existing functions for dot products and summation, with the minimum coefficient used for cloud determination.

Cloud Removal: The template method requires the standard limb-darkening profile. Parallel division yields cloud transmittance with solar features. CUFFT functions transform the image to frequency domain, where a Butterworth low-pass filter is generated in parallel and multiplied with the frequency-domain image to filter high frequencies. Inverse Fourier transform converts the filtered image back to spatial domain, producing cloud transmittance without solar features. Finally, the centered cloud-contaminated image is divided by the transmittance in parallel to obtain the restored image.

Important parameters are set with default values based on experimental statistics, with user-adjustable ranges provided in the interface.

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4. System Performance Testing

The test computer configuration includes: Windows 7 OS, Microsoft Visual Studio 2010, CUDA 6.5, Intel Pentium E5200 CPU, and Nvidia GeForce GT 430 GPU. Processing times for major operations on the GPU were measured using the 2048×2048 cloud-contaminated image from Figure 1(b).

shows the GPU processing time for each operation. The total GPU processing time is 376.1 ms, while CPU operations (reading images, data transfer, display) take 342 ms, yielding a total system time of 718 ms. This meets the real-time display requirement for 1-minute observation intervals.

Fourier transforms and frequency-domain filtering dominate the computation, consuming 52.9% of total GPU time. The GPU' s parallel processing capability for high-density image data is fully demonstrated.

Optimization Details: While CUDA provides sorting functions for arbitrary-length data, they require data placement in vector containers and cannot achieve inter-dataset parallelism, resulting in long sorting times (0.5 ms per dataset, 26.8 ms total). Bitonic sorting offers higher intra-dataset efficiency and enables inter-dataset parallelism. Although constrained to power-of-2 lengths, setting the polar angle dimension to 512 allows parallel processing of 12 datasets with minimal total time (21.7 ms).

Generating the Butterworth filter on the GPU takes 45.6 ms. Attempting to pre-compute and load the filter from disk proved slower (77 ms total) due to I/O overhead, making on-GPU generation preferable despite the computational cost.

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5. Discussion and Limitations

The system has several limitations: (1) The recoverable cloud detection algorithm may fail for symmetrically and uniformly distributed cloud coverage, though such cases are extremely rare; (2) Frequency-domain filtering exhibits edge effects due to large intensity gradients at the solar limb. Increasing the filter cutoff frequency removes more cloud contamination but also eliminates solar activity details.

The system' s primary objective is real-time display during observations, emphasizing processing speed over high-precision restoration. While restored data is saved, high-precision processing of cloud-contaminated images for scientific analysis may require parallel implementation of multi-scale morphological filtering methods. The system could also be extended to other full-disk solar images beyond H . Future work should verify whether the detection and restoration principles apply to partial-disk solar images, potentially developing corresponding GPU-based software.

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Note: Figure translations are in progress. See original paper for figures.