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How to apply the Geospatial Data Abstraction Library (GDAL) properly to parallel geospatial raster I/O?

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Abstract: Input/output (I/O) of geospatial raster data often becomes the bottleneck of parallel geospatial processing due to the large data size and diverse formats of raster data. The open-source Geospatial Data Abstraction Library (GDAL), which has been widely used to access diverse formats of geospatial raster data, has been applied recently to parallel geospatial raster processing. This paper first explores the efficiency and feasibility of parallel raster I/O using GDAL under three common ways of domain decomposition: row-wise, column-wise, and block-wise. Experimental

results show that parallel raster I/O using GDAL under column-wise or block-wise domain decomposition is highly inefficient and cannot achieve correct output, although GDAL performs well under row-wise domain decomposition. The reasons for this problem with GDAL are then analyzed and a two-phase I/O strategy is proposed designed to overcome this problem. A data redistribution module based on the proposed I/O strategy is implemented for GDAL using a message-passing-interface (MPI) programming model. Experimental results show that the data redistribution module is effective.

Keywords: geospatial raster data, parallel I/O, Geospatial Data Abstraction Library (GDAL), message passing interface (MPI)

1. Introduction

With the rapid growth of affordable parallel devices, parallel geospatial raster processing has become more widely used in dealing with increasingly massive geospatial raster datasets (e.g., Guan and Clarke 2010; Qin and Zhan 2012; Maulik and Sarkar 2012). However, two challenges still generally exist in the input/output (I/O) part of parallel geospatial raster processing. The first is the massive size of raster data, whose movement between fast main memory and slow disk storage often becomes the performance bottleneck of parallel geospatial raster processing. The second challenge is the diversity of geospatial raster data formats. Although there are

presently at least several dozen often-used raster file formats, existing parallel geospatial raster-processing programs often support only a very few file formats, which limits their practical applicability.

Some studies have proposed to address the challenge of massive raster data by providing a parallel API to access a single file storing massive raster data in a specific format (e.g., Hierarchical Data Format v5 (HDF5), Parallel Network Common Data Format (PnetCDF), and Parallel Input-Output System (PIOS) (Shook and Wang 2011)). These studies have mainly focused on I/O performance while paying little attention to the challenge of diverse geospatial raster data formats.

The Geospatial Data Abstraction Library (GDAL, http://www.gdal.org/, current version number 1.9.2) (Warmerdam 2008), which is an open-source tool providing a single abstract data model to read and write a variety of geospatial raster data formats, has been widely used in serial raster-processing applications. Some recent studies (e.g., Wang *et al.* 2012) have applied GDAL to parallel geospatial raster processing in a serial I/O mode for accessing raster data, i.e., a master process takes charge of the entire I/O process between external and internal memory, and other work processes access the data by communicating with the master process (Figure 1). However, this approach lacks parallelism and often creates a bottleneck when the size of the raster file exceeds the memory capacity of a single compute node.

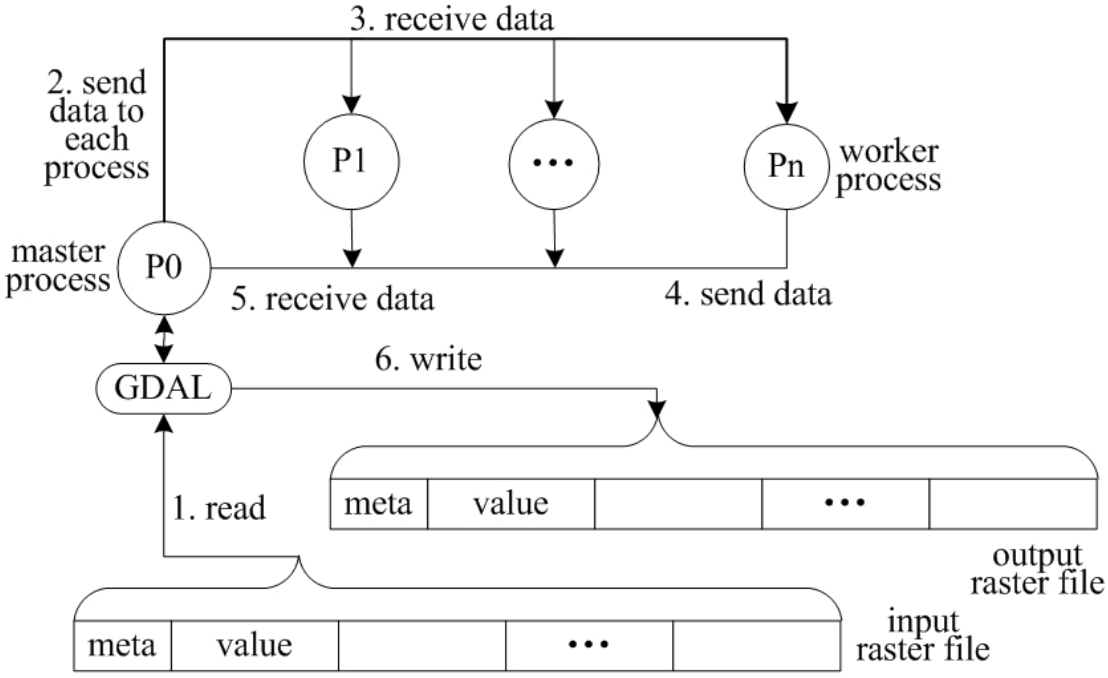

Figure 1. Serial raster I/O mode of applying GDAL to parallel geospatial processing.

Parallel raster I/O mode permits each process to access directly a part of the data stored in external memory, based on a kind of domain decomposition in which the data domain being processed is decomposed into subdomains. There are three commonly used, straightforward ways of domain decomposition: row-wise, column-wise, and block-wise. The parallel raster I/O mode could overcome the single-bottleneck problem in the serial raster I/O mode. However, there are few literatures on using GDAL in parallel I/O mode.

This paper first explores the efficiency and flexibility of using GDAL in parallel raster I/O mode under the three common ways of domain decomposition. Experimentation shows that parallel raster I/O using GDAL cannot work well under two among the three ways of domain decomposition. Then a solution to this problem is proposed.

2. Using GDAL in parallel raster I/O mode

When using GDAL in parallel raster I/O mode (Figure 2), the master process first uses GDAL to extract the metadata (e.g., spatial extent, projection) from a raster file and creates a corresponding empty output file. Then, following a specific domain decomposition approach, the master process sends the spatial extent information of each subdomain to the corresponding work process. Based on the subdomain information received, each process uses GDAL to open the shared input raster file and to read the subdomain data using the *RasterIO()* function in GDAL. After computation, each process uses GDAL to open the shared output raster file to write the results using the *RasterIO()* function. This parallel raster I/O mode could avoid certain problems in serial I/O mode, such as the single-bottleneck problem and the overhead for data distribution between the master process and the work processes.

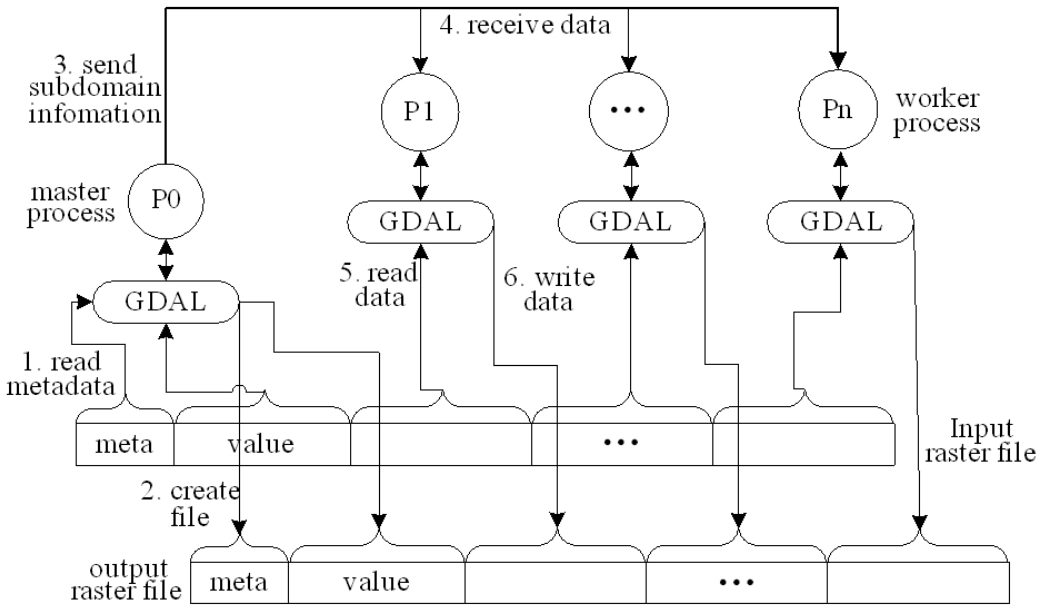

Figure 2. Parallel raster I/O mode of using GDAL for parallel geospatial processing.

3. Problem in parallel raster I/O using GDAL

In this section, the problem in parallel raster I/O using GDAL will be revealed by an experiment.

3.1. Experimental design

Based on the message passing interface (MPI) programming model, parallel raster I/O mode of using GDAL (called *GDAL_PIO*) was implemented. An experiment was designed to evaluate the efficiency and flexibility of *GDAL_PIO*. In this experiment, there is actually no computation, only read and write operations on the raster file, because this study concerns only I/O issues.

GDAL_PIO was tested on an IBM SMP cluster with 140 server nodes (including 6 I/O server nodes and 134 compute nodes). Each server node consists of two Intel Xeon (E5650 2.0 GHz) six-core CPUs and 24 GB DDRIII memory. The test raster data have a dimension of 23300×27825 cells. The data are stored as a file in GeoTiff format on I/O server nodes and shared between compute nodes through the General Parallel File System (GPFS).

Efficiency is evaluated by measuring the runtime to read and write data from/to a raster file with a specific format using *GDAL_PIO* (called I/O time). The time to create the output file is not counted in I/O time. Flexibility is evaluated by determining whether *GDAL_PIO* can work well under different domain decomposition approaches (row-wise, column-wise, and block-wise).

3.2. Experimental results

The experimental results show that *GDAL_PIO* with row-wise domain decomposition is efficient (Figure 3). The I/O time using *GDAL_PIO* decreases when the number of processes increases from 1 to 8. The I/O time for *GDAL_PIO* with 8 processes is about half that with one process. The I/O time for *GDAL_PIO* with 16 processes is longer than with 8 processes, but is still shorter than with 4 processes.

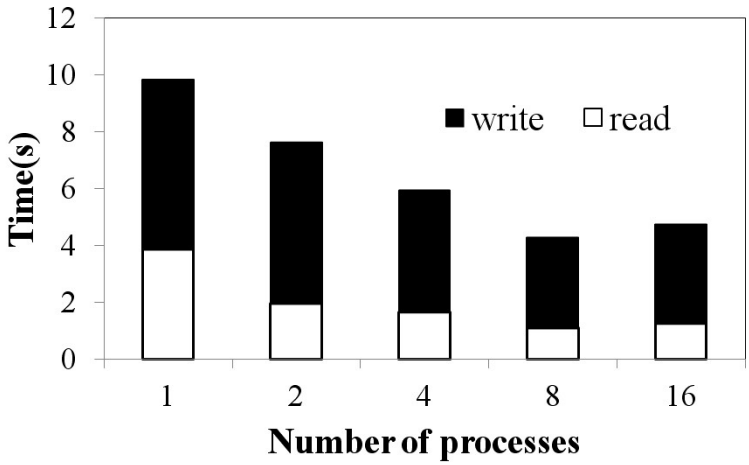

Figure 3. Runtimes for read and write operations of *GDAL_PIO* using row-wise decomposition when the number of processes varies from 1 to 16 (only one process per compute node).

However, using *GDAL_PIO* with column-wise or block-wise decomposition is highly inefficient, that is, almost 5–15 times slower than using *GDAL_PIO* with row-wise decomposition (Figure 4a). Moreover, *GDAL_PIO* with column-wise or block-wise decomposition produced incorrect results in which some areas with values were output as having no data (the black holes in Figure 4b). The results for

GDAL_PIO with row-wise decomposition were correct. Therefore, the experimental results show that *GDAL_PIO* lacks flexibility.

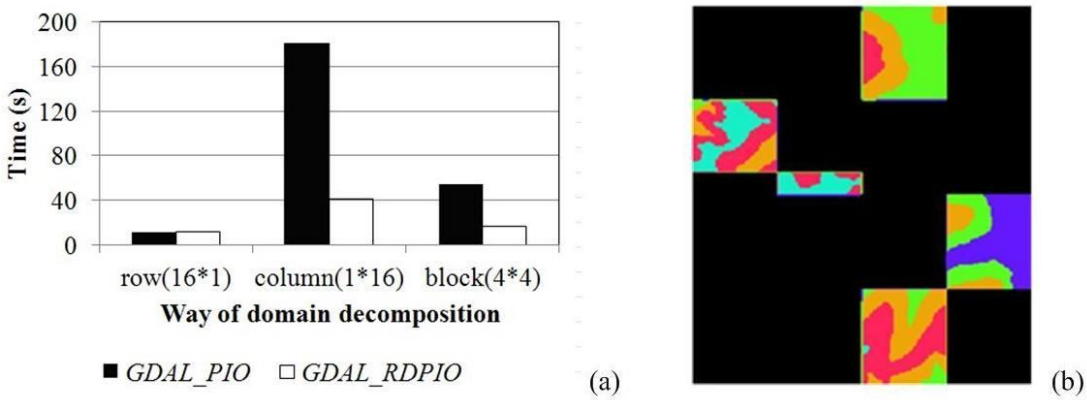

Figure 4. Performance of *GDAL_PIO* and *GDAL_ RDPIO* (an implementation of the new parallel raster I/O strategy using GDAL proposed in this paper, described later) executed on a cluster with a test raster file in GeoTiff format: a) I/O times using *GDAL_PIO* and *GDAL_ RDPIO* under three ways of domain decomposition (16 processes created on 16 compute nodes); b) example of incorrect results from *GDAL_PIO* with block-wise decomposition (black areas are blocks where results were missed).

3.3. The reason for the problem in parallel raster I/O using GDAL

This poor efficiency of *GDAL_PIO* with column-wise and block-wise decomposition is attributable to the fact that the processes are accessing several non-contiguous sections of a shared raster file. From the viewpoint of the user, a raster data file is a two-dimensional array. Therefore, when *GDAL_PIO* is executed with column-wise or

block-wise decomposition, each process calls the *RasterIO()* function in GDAL only once to access data, similarly to the situation with row-wise decomposition (Figure 5a). However, the raster data saved in disk are actually re-organized row-by-row as a contiguous linear stream of values which starts from the upper left corner cell in the raster array and ends with the lower right corner cell (Figure 5b). As a result, each process must access several non-contiguous sections of the file when *GDAL_PIO* is executed with column-wise or block-wise decomposition. This situation means that each call to the *RasterIO()* function will involve multiple I/O requests. For a large raster array, the large number of small I/O requests generated from column-wise or block-wise decomposition will considerably augment the I/O time (Figure 5c).

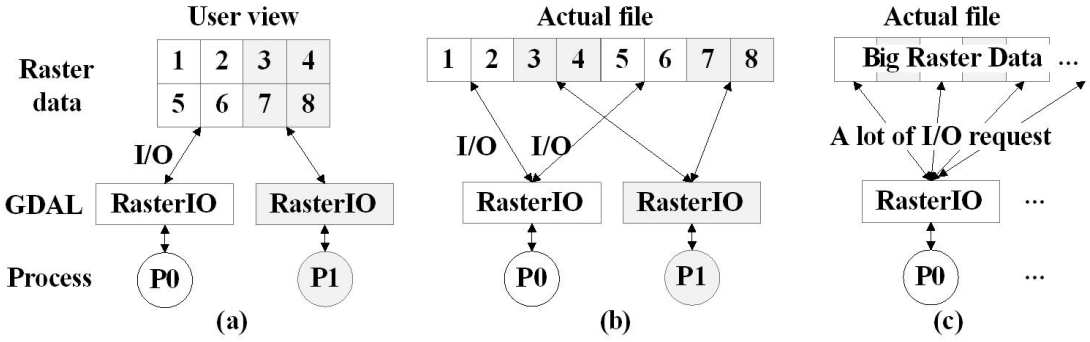

Figure 5. Analysis of the reason for the poor efficiency of *GDAL_PIO* with column-wise and block-wise decomposition: a) I/O requests from only two processes using GDAL to access a 2×4 raster array with column-wise decomposition (from the viewpoint of the user); b) the actual I/O requests in case a); c) a large number of small I/O requests by each process with column-wise decomposition of a large raster data array in reality.

168 Incorrect results from *GDAL_PIO* with column-wise and block-wise
169 decomposition are attributable to the caching mechanism in GDAL. GDAL maintains
170 in memory the cache blocks fetched from the raster file and ensures that a second
171 attempt to access the same block will be served from the cache instead of from the file.
172 Such a caching mechanism makes the cache block to be the smallest size of each I/O
173 request. The width of the cache block in GDAL is often equal to the raster width. In
174 this situation, incorrect results will arise when different processes try to write the
175 cache block to the same region of a shared raster file.

176 Consider a simple case in which two processes are writing to two subdomains of
177 a raster file with column-wise decomposition (Figure 6a). In this case, the width and
178 height of the GDAL cache block are 4 and 1 respectively. Process *P0* first creates a
179 cache block in memory (black cell means no data), initializes it from the disk file, and
180 then sends the output value to the cache block (Figure 6b). Meanwhile, process *P1*
181 performs the same tasks as *P0* (Figure 6b). After the output value has been sent to the
182 cache block, each process writes the cache block in memory to the same region of the
183 raster file on disk. As shown in Figure 6c, the file is first written by process *P0* at time
184 1 and later is rewritten by process *P1* at time 2. Therefore the final results file
185 contains cells without data (Figure 6c), as shown by the experiment described earlier
186 (Figure 4b). In fact, the results file will always contain some cells with no data unless
187 the processes write the cache block serially to the same region of the file.

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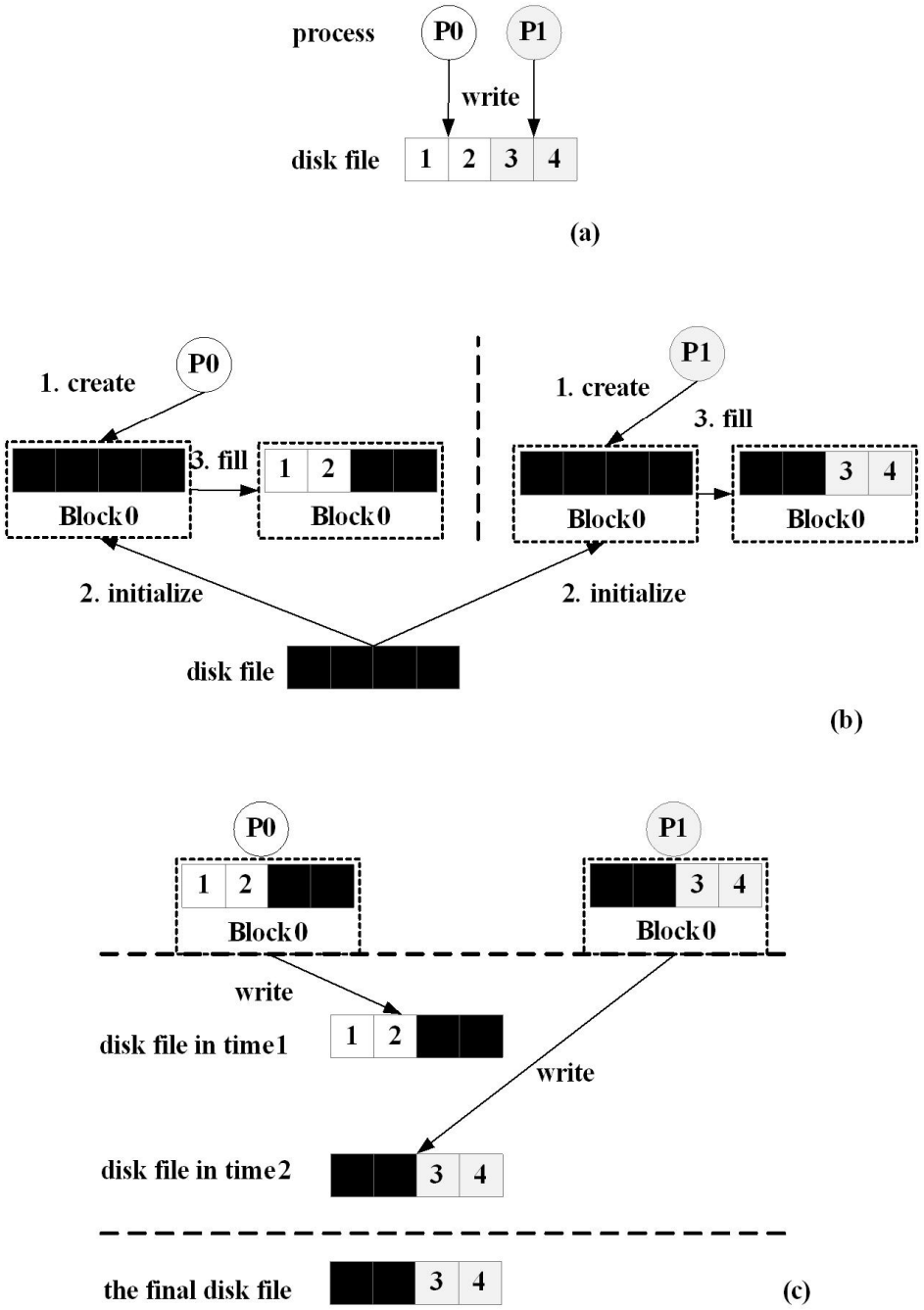

Figure 6. Analysis of the reason for the incorrect results produced by *GDAL_PIO* with column-wise and block-wise decomposition (black cell means no data): a) two processes are writing to respective subdomains of a raster file with column-wise decomposition (the size of the GDAL cache block is 1×4, i.e., one row of the raster); b) each process prepares data in the cache block; c) each process writes the cache block in memory to the same region of the shared disk file.

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197 4. Improvement based on a two-phase I/O strategy

198 This section introduces a “two-phase I/O” strategy which is a suitable solution for the
199 problems in *GDAL_PIO* with column-wise and block-wise decomposition. The
200 two-phase I/O strategy was first proposed by Rosario (1993) and was implemented in
201 MPI I/O for a much more efficient use of the I/O subsystem (Thakur *et al.* 1999). The
202 basic idea of this strategy is to redistribute data among the processes by combining a
203 large number of small I/O requests into a small number of large continuous I/O
204 requests.

205 Based on the two-phase I/O strategy, a data redistribution module for GDAL was
206 designed. This module provides two features. The first is to reduce the number of I/O
207 requests by combining small I/O requests into large continuous I/O requests through
208 inter-process communication. This should be efficient because I/O operations are
209 often more time-consuming than inter-process communication. The second feature is
210 to avoid possible conflict among processes which might be trying to write the cache
211 block to the same region of the shared raster file.

212 Figure 7 shows an example of a write operation involving two processes and
213 using such a data redistribution module. The two processes first exchange their local
214 individual I/O requests to form new I/O requests. Then according to the new I/O
215 request, inter-process communication is used to redistribute the data so that each
216 process has one contiguous chunk of data. This means that the data for each process

are available to be written to the disk file with only one I/O request. Moreover, because these two processes write their respective cache blocks to different regions of the shared raster file, there is no conflict.

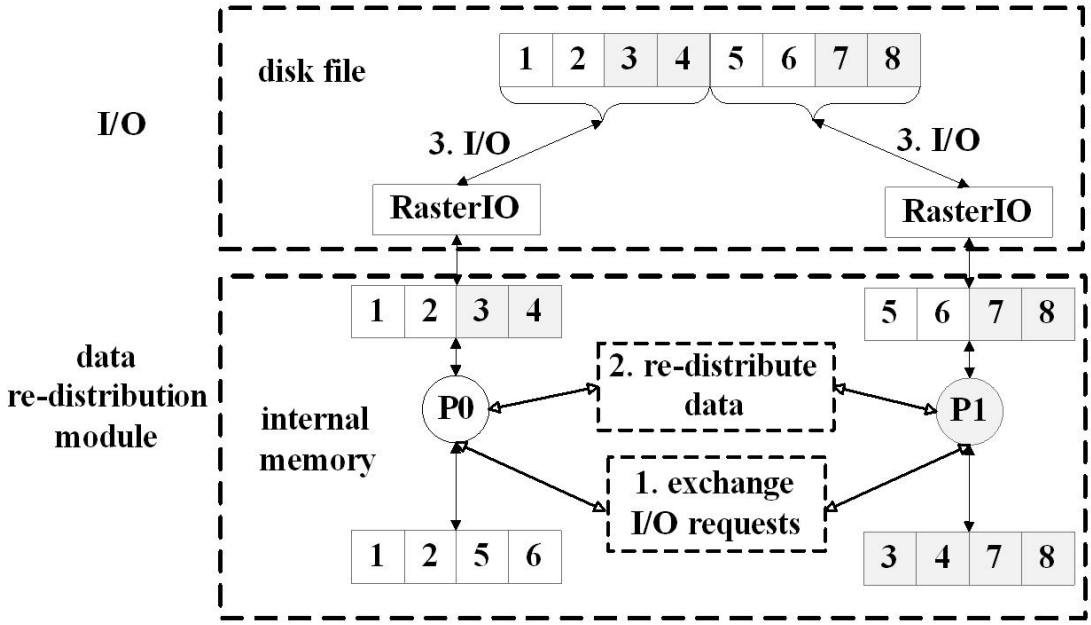

Figure 7. Using GDAL with a data redistribution module based on the two-phase I/O strategy.

5. Experiment and results

MPI was used to implement the proposed data redistribution module based on the two-phase I/O strategy for using GDAL in parallel raster I/O mode (called *GDAL_RDPIO*, short for "*ReD*istribution *P*arallel *I/O*"). The test data and test environment are same as for the earlier experiment (see Section 3.1).

The experimental results show that *GDAL_RDPIO* was about four times faster than *GDAL_PIO* when column-wise or block-wise decomposition was used (Figure

232 4a). With row-wise decomposition, *GDAL_RDPIO* and *GDAL_PIO* achieved almost
233 the same I/O times. The results from *GDAL_RDPIO* with each of the three data
234 decompositions are correct. *GDAL_RDPIO* shows satisfactory efficiency and
235 feasibility.

236 6. Conclusions

237 This paper first explores the parallel raster I/O mode of using GDAL to access
238 geospatial raster data. Experimental results show that parallel raster I/O using GDAL
239 under column-wise or block-wise domain decomposition is highly inefficient and
240 cannot achieve correct output. After analysis of the reason for the problems with
241 parallel raster I/O using GDAL, a two-phase I/O strategy was used to design a data
242 redistribution module for GDAL to fix these problems. MPI was used to implement
243 this data redistribution module for GDAL. Experimental results show that the
244 proposed data redistribution module provides an efficient solution to effective
245 application of GDAL to parallel geospatial raster I/O.

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