Architecture of the new MARS server

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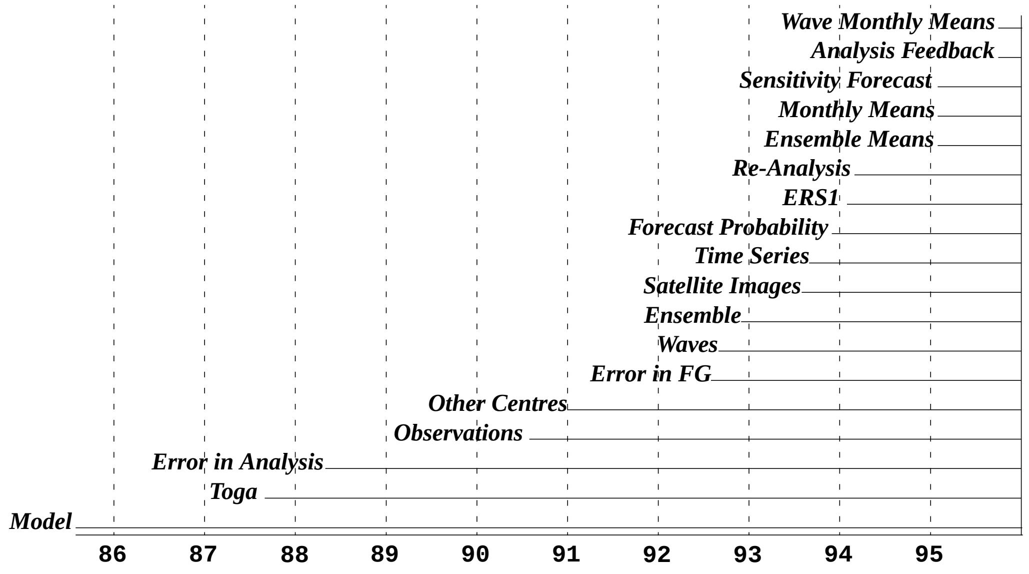
1. Introduction

Since 1985, the ECMWF Meteorological Archival and Retrieval System (MARS) has grown both in size and diversity. At its start in 1985, the operational archive was growing at 70 Mbytes/day. In 1996, the growth rate was 125 Gbytes/day of operational data and 7 Gbytes/day of research data, the total archive was 22 Tbytes. The number of individual items archived is also very large: 120,000 operational fields/day, 140,000 reports/day and 200,000 research fields/day.

Figure 1 shows the various data types that are in MARS and the year in which they have been introduced. We actually have more data, for example we have observations since 1979, but the data type “observation” was added to MARS in july 1990. Earlier data was them back-archived. Since this chart was drawn, new types have been added: 4D variational analysis, climatological simulations, seasonal forecasting, ensemble tubes and much more. As you can see, the curve shown is exponential, and we add new types more and more often.

Figure 1: MARS - Data Types



We still have to add ocean models, coupled models, private datasets,... The list is endless.

MARS is used in batch from the super-computers, interactively through Metview and remotely from the Member States. Every day, 30,000 requests are processed, 1,500,000 fields and 100 Gbytes are moved.

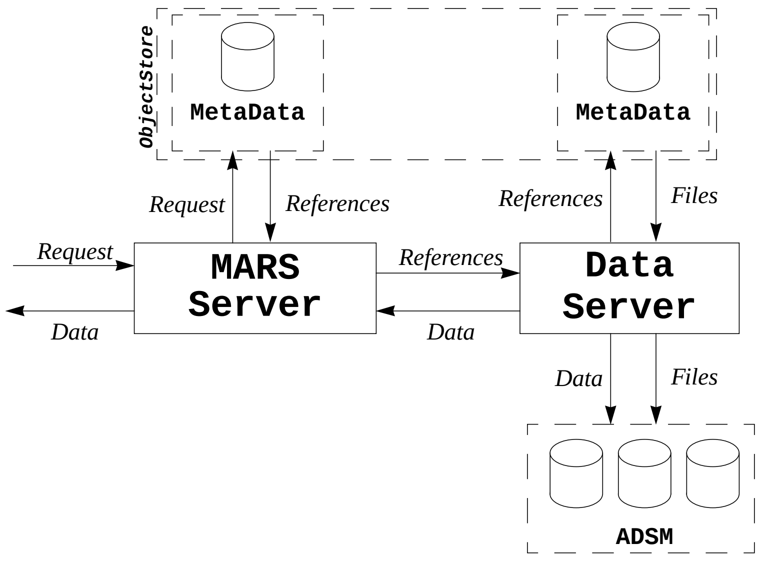
In order to cope with this growing archive and the ever changing requirements, a project was set up in 1996, called the DHS project (Data Handling System). MARS was totally redesigned to run on a Unix platform. It is written in C++ and uses ObjectStore to store its metadata and ADSM to store the actual data.

The new MARS had to be compatible with the old system. It has to provide a service for the next 10 years, and like every computer program, it has to be efficient, scalable and flexible. This paper describes how we try to achieve those goals.

2. Decoupling physical and logical organisation of the data

From the experience gained with the previous MARS systems, we knew we could build a system scalable it we could decouple the physical organisation of the data from its logical organisation. For that we split the system in two parts. The first part, the MARS Server, has a semantic knowledge of the data. It knows what a meteorological field is, what a forecast is. The second part, the Data Server, has a physical knowledge of the data. It knows if a piece of data in on tape, on disk or cached. Figure 2 shows the architecture of MARS.

Figure 2: Architecture



The MARS Server does not handle files but data references. When a user request is processed, the MARS Server translates it in a list of data references, that are passed to the Data Server. The Data Server translates data references in actual files and returns the data.

By using this design, we have a system that is independent from the underlying hardware and from the underlying software (ADSM). The data can be physically re-organised without any impact on the system. Data files are split or joined, moved from disk to tape without a need for the MARS Server to know about it. Something else we have learnt from the previous system is that the fewer the files we have, the more manageable the system is. Most of the existing systems have problems managing more that a few million files. With this architecture, we can reduce the number of files by merging them into larger files. Nowadays, we have more than 30 Tbytes in less than 200,000 files.

3. The metadata

The metadata is “the data that describes the data”. In MARS, the data are fields or observations. The metadata is the data that knows where is which field or observation. This metadata is stored in an object oriented database, managed by a commercial product called ObjectStore. As we saw earlier, we need to split the logical organisation of the data form its physical organisation. This split will be reflected in the metadata. In order to define this metadata, we first need to have a look at the data and answer the following question:

3.1 What is a meteorological field?

For MARS, a meteorological field is the smallest addressable object. It is defined by various attributes such as those shown in the following table:

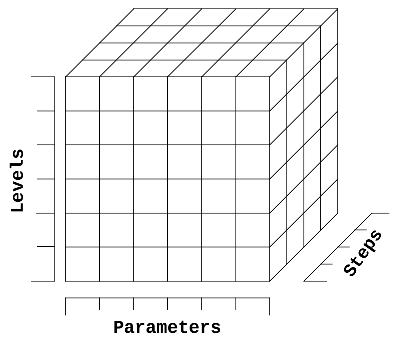
Attribute	**Value**
Class	Operational
Version	1
Stream	Daily archive
Parameter	Temperature
Level	1000 hPa
Date	1993-08-10
Base Time	12Z
Time Step	120 H
Member	42

The attributes may be different for different data types. For example, the `number` attribute is only used to select a specific forecast number in an EPS (Ensemble Prediction System).

3.2 Archive objects

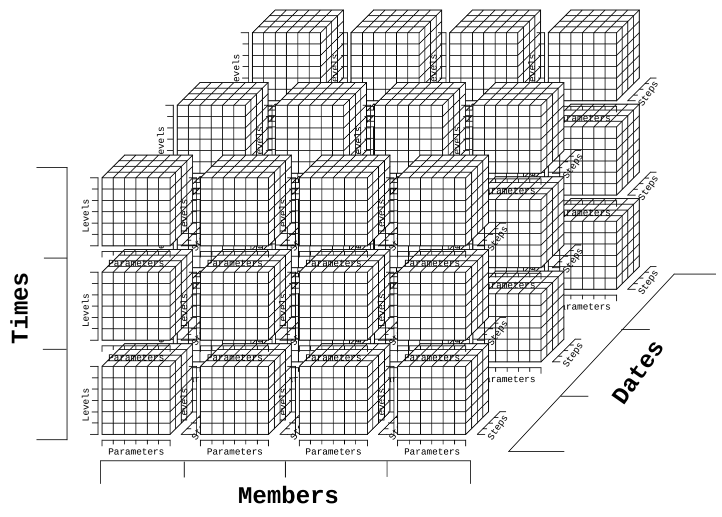
There are too many fields to store them individually. We need to group them into logical entities such as “a forecast”, “a month of analyses” or “a research experiment”. This provides a natural data co-location for a faster access to related data. Those entities are called *archive objects*. We can stack all the fields for a forecast in a “cube” as shown in Figure 3. We group the fields using three attributes: `level`, `parameter` and `step`. This would represent a single forecast, for a given date, a given base time, and a given version. The three attributes are the three dimensions of the *archive object*.

Figure 3: Archive object



Because we group the fields using more than three attributes, the archive objects are actually hypercubes. Figure 4 is an attempt to draw a six the dimension hypercube that would represent all the fields of all the forecasts of an EPS for a month.

Figure 4: Archive objects are hypercubes



3.3 Shapes and Layouts

We split the description of an *archive object* into its *shape* and its *layout*. The shape will be:

- Its meteorological content.
- Its logical organisation.
- Part of MARS metadata.

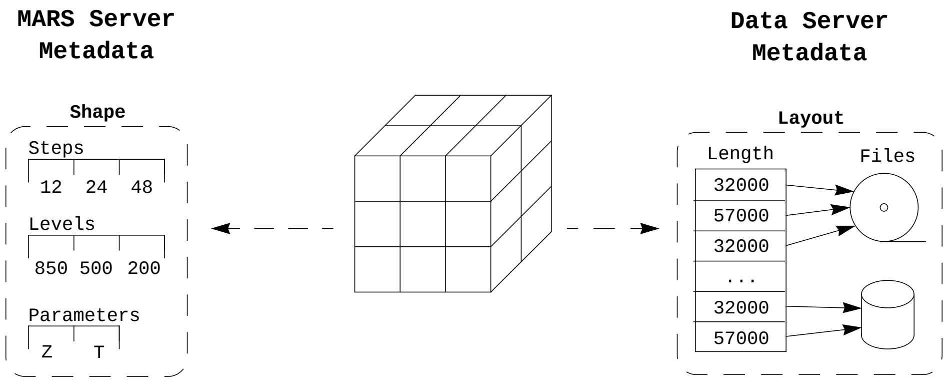
And its layout will be:

- Its physical organisation.
- Its physical location.
- Part of the Data Server metadata.

Figure 5 shows how we perform this split: the archive object is represented as a cube. The MARS Server metadata is simply the list of each dimension of the cube. In this case, three axes and their labels. This is called the “shape” of the archive object.

The Data Server metadata will contain the size of each field, the file it is in, and its offset in this file. This is the “layout” of the archive object. Each layout is given a unique identifier that will be save by the MARS Server with the shape.

Figure 5: Shapes and Layouts

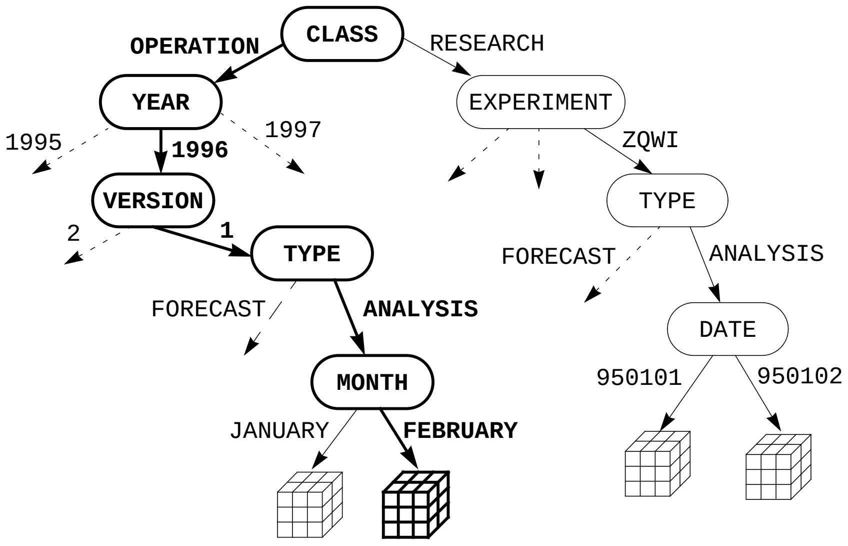


3.4 MARS Server metadata

All the shapes are organised in a tree fashion, as shown in Figure 6. The nodes of the tree are defined by the attributes that are not used to describe the dimensions of the archive objects.

When a user request is received, it is used to navigate the tree. The highlighted path in Figure 6 corresponds to a request for some fields from the operational analysis of february 1996.

Figure 6: MARS Tree

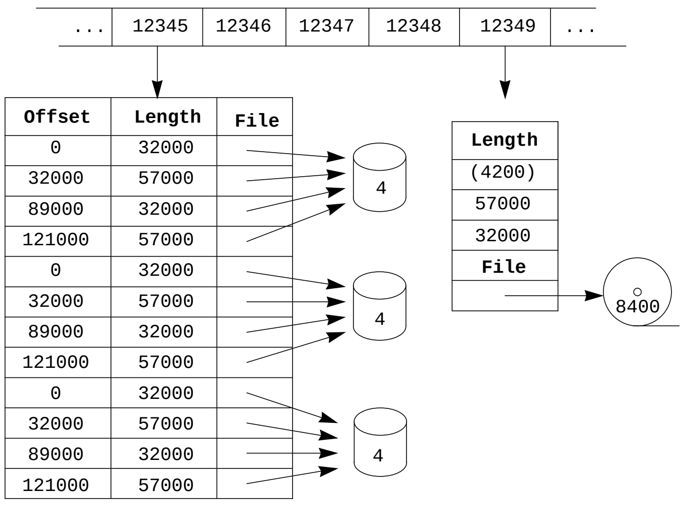


Because the design is object oriented, each node and each shape can be different (polymorphism). New nodes can be added later, as new attributes are invented and new shapes can be added latter, as new data types are created. The branches of the tree can all be different and the tree can span several physical databases

3.5 Data Server Metadata

The layouts are all organised in a large table, using their unique identifier as an index (Figure 7). A layout can be fully expanded, in this case it is itself a three column table. The first line correspond to the first field, the second line to the second field and so on. A layout can also be compacted. Most of the time, the fields have a fixed size, so we can use a simple run-length encoding scheme to reduce the size of the metadata. In Figure 7, the layout `12349` represents 8400 lines compacted into 3. The first one is the repeating factor of the two next lines.

Figure 7: Data Server Metadata



Again, the design being object-oriented, the layouts are polymorphic objects. Future type of layout may be introduced without any change code. The files also are polymorphic objects: support for new media or file storage systems will be done without difficulty. A layout can span several files, tape or disk and a file can be shared amongst several layouts.

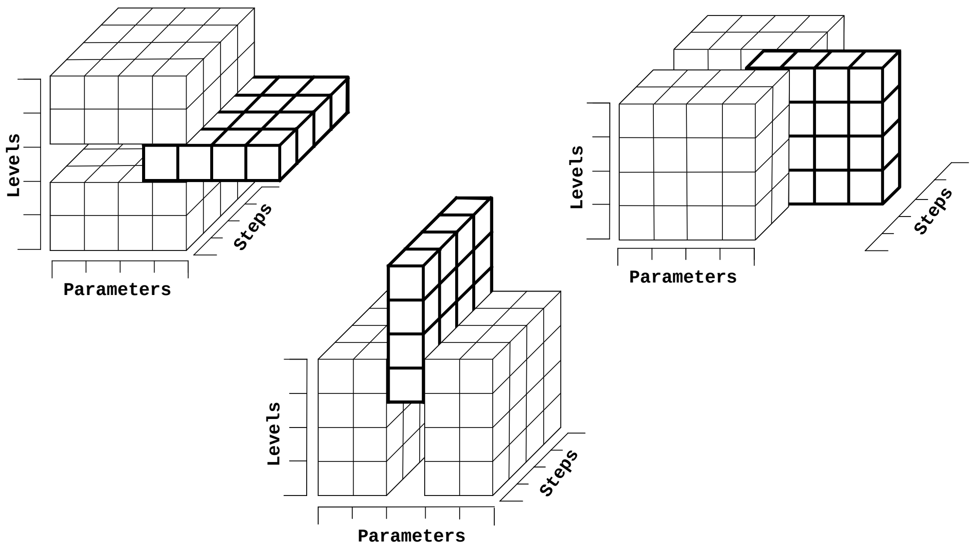
Each file knows how many layout lines point to them (the numbers shown in Figure 7). This is called reference counting and is use to perform garbage collection: files that are not pointed to are automatically deleted.

3.6 Adding a new fields in an existing archive object

The design described above gives us a new feature that did not exist in the previous system: incremental archiving. A field can be added latter to an existing archive object. If one of is attributes has a new value, it automatically inserted.

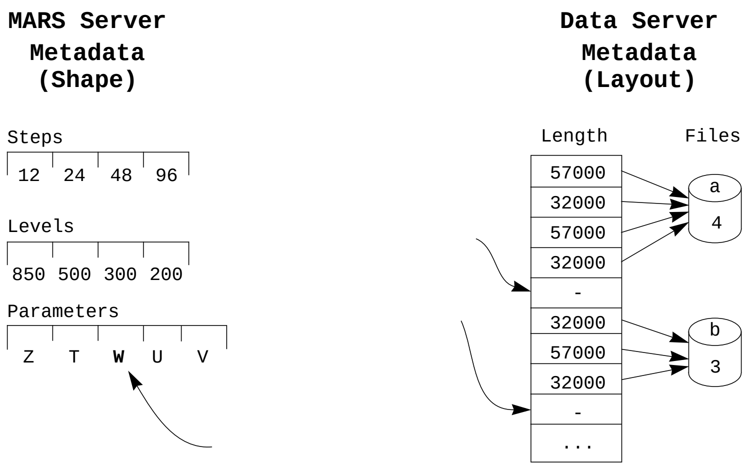
Is an archive object has three dimensions, there are three ways it can grow, as shown in Figure 8:

Figure 8: Reshaping hypercubes



In general there a *n* ways to grow a *n* dimension hypercube, by inserting a *n-1* dimensions hyperplan. It is a lot easier to perform the same insertion on the metadata once it is split. If we archive a new parameter `W` in an archive object (Figure 9), we simply insert a string in a array (MARS Server) and some empty slots in a other array (Data Server).

Figure 9: Updating metadata



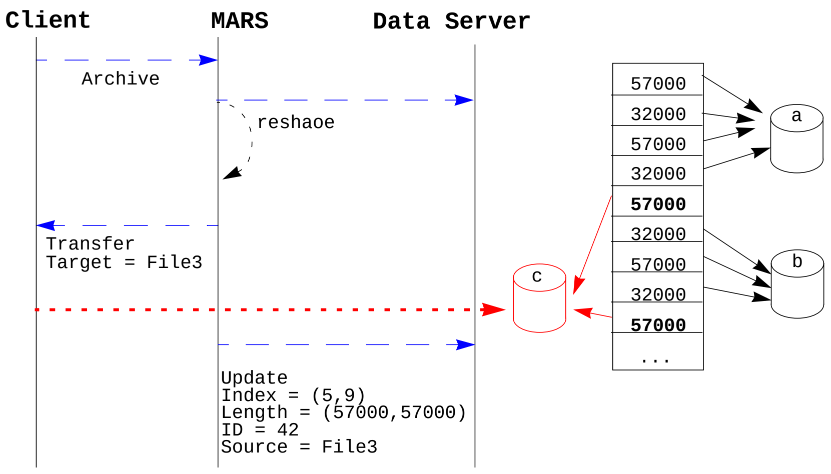
4. MARS in action

4.1 Archiving

When an archive request is issued from a client, the request visits the tree (Figure 6) until it reaches a shape. If it does not, the tree is grown accordingly, and a new empty shape is added. Figure 10 shows an incremental archive. The names at the top are the various components involved. The time flows from top to bottom. The dashed arrows are the messages sent between the components. The dotted arrows are the data transfers.

File `a` and `b` contains data that has been been archived earlier. The data is transferred from the client machine into a disk file `c`. This file contains two 57000 byte long fields. The layout is resized to accommodate the new fields, and it is updated to point to file `c`. The data held in `c` in still on disk, and said to be in “pre-archive” stage.

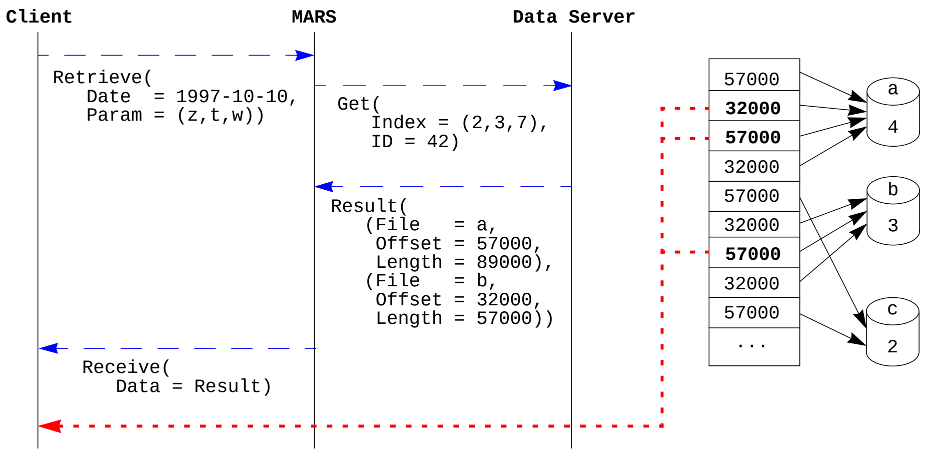
Figure 10: Incremental archiving



4.2 Retrieving from disk

While the data is still in “pre-archive” stage, retrieving is very fast. As in archive, the MARS tree is visited in order to find one or more shape matching the user request. The request is translated into a list of indexes in the layout, and the data is read directly from the disk files and sent to the user.

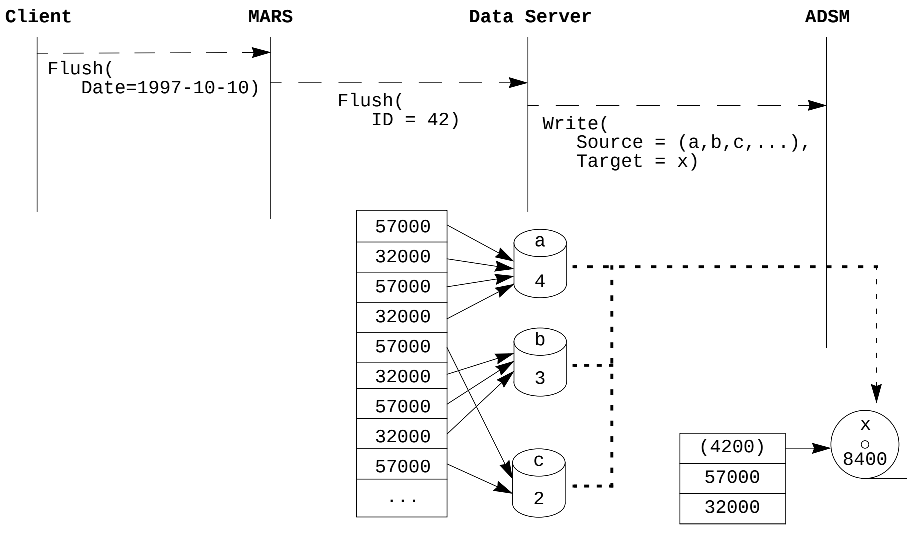
Figure 11: Retrieving, data is on disk



4.3 Flushing

Flushing occurs when an archive object is complete, or when the disks are full. A flush request write all the fields that are in the “pre-archive” stage on tape. The layout will be updated to reflect the change, an the data on-line will be deleted. The layout is then compacted. Figure 12 shows that the layout 42 is composed of files a, b, c and more. Those files are merged into a single tape file x. The layout is compacted from 8400 lines to three lines, noticing that the field sizes are 4200 times 57000 and 32000 bytes long. Once the tape exist, the archive object is no longer in the “pre-archive” stage.

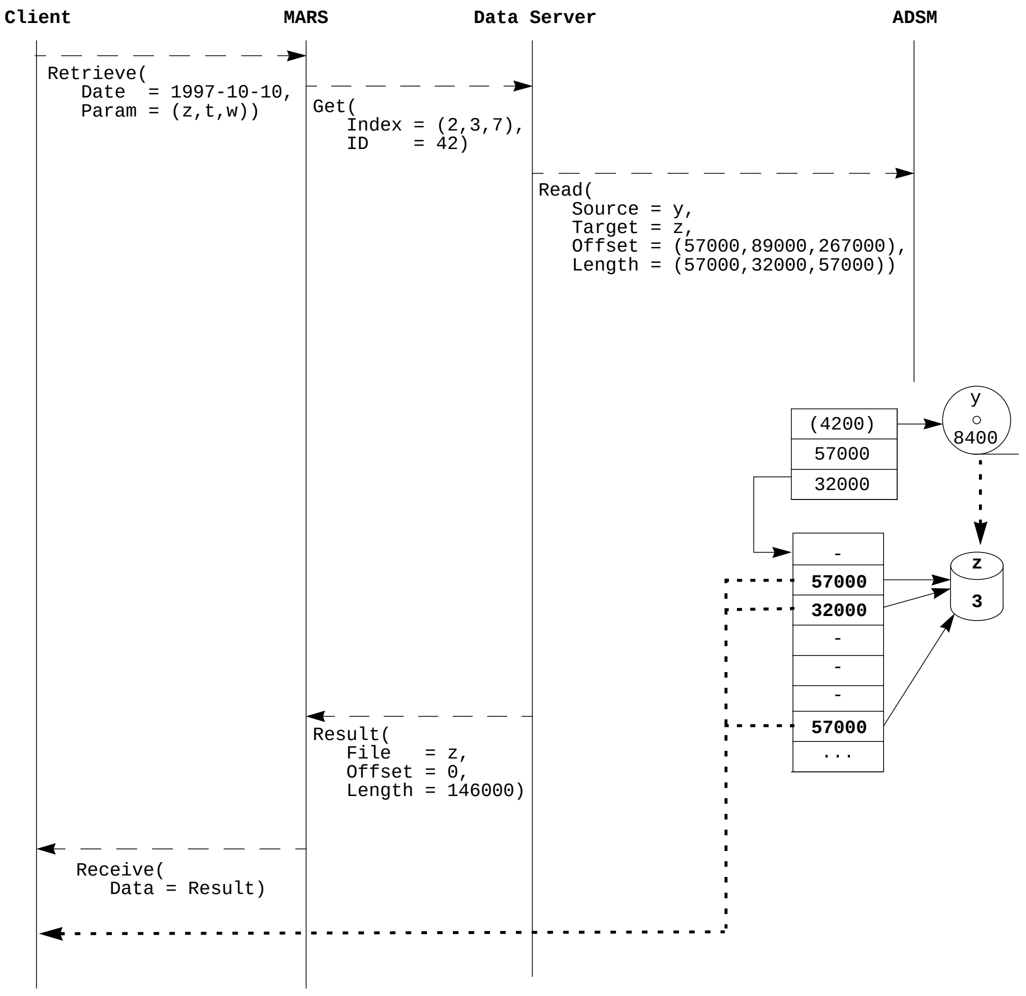
Figure 12: Flushing



4.4 Retrieving from tape

When the data is on tape, it must be copied first to a set of disks that are the MARS cache. ADSM is very useful as it can read only portions of a tape file, so only the requested data will be cached. When data is retrieve from a tape, a temporary layout, called the "cache layout" is created. This layout contains the pointers to all the data that has been cached for a particular archive object. Figure 13 show the flow of request and data. The requested data is copied from tape `y` into cache file `z`. The data is then sent to the user as describe previously. The cache is emptied using a least recently used algorithm.

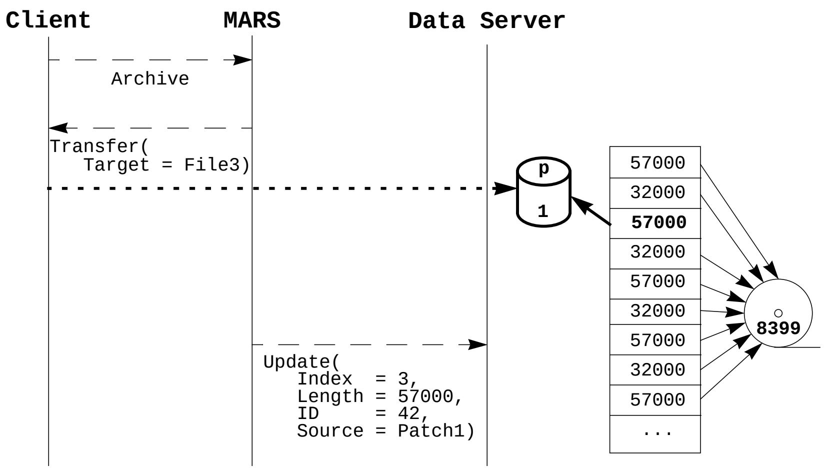
Figure 13: Retrieving data that is on tape



4.5 Patching

To correct a field that is wrong, the user simply need to archive it again. If the layout has been flushed, it is mutated in its expanded shape again, and the field is simple added as for a normal archive (Figure 14). The reference counting of the tape file is decremented. If it reaches zero, that mean that all the fields have been replaced, and the tape file is automatically deleted. The layout can be flushed again. In this case, only the new data will be written to tape. The layout will now point to several tape files. When a layout is too fragmented (it points to too many tape files) it can be defragmented by copying all of its data back to disk and flushing it again, into a single tape file.

Figure 14: Patching



5. Conclusion

After one year of service, the new MARS keeps is promises. It now contains 520 millions of meteorological fields, representing 32 Tbytes in only 180,000 files. More than 7 millions requests have been processed. The metadata database represents 0.03% of the size of the archive.

This would not have been possible without an object oriented design, the metadata being too complex for a relational approach, and yet very simple for an object oriented approach. The system is extendable, new data types can be supported and the underlying storage management can evolve.