Astronomical imagery: Considerations for a contemporary approach with JPEG2000

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The new wide-field radio telescopes, such as: ASKAP, MWA, LOFAR, eVLA and SKA, will produce spectral-imaging data-cubes (SIDC) of unprecedented size—in the order of hundreds of Petabytes. Servicing such data as images to the end-user in a traditional manner and formats is likely going to encounter significant performance fallbacks. We discuss the requirements for extremely large SIDCs, and in this light we analyse the applicability of the approach taken in the JPEG2000 (ISO/IEC 15444) standards. We argue the case for the adaptation of contemporary industry standards and technologies versus the modification of legacy astronomy standards or development of new standards specific to astronomy only.

1. Introduction

Spectral-imaging data-cubes (SIDCs), from the new radio telescopes that are currently in various stages of construction or commissioning – Australian Square Kilometre Array Pathfinder (ASKAP) (DeBoer et al., 2009), Murchison Widefield Array (MWA) (Tingay et al., 2013), LOFAR (van Haarlem et al., 2013), MeerKAT (Booth et al., 2009), eVLA (Perley et al., 2011) – are expected to be in the range of tens of GBs to several TBs. The Square Kilometre Array (SKA) Design Reference Mission, SKA Phase 1 (Lazio, 2013), defines at least one survey, namely the “Galaxy Evolution in the Nearby Universe: HI Observations”, for which the SKA pipeline will produce hundreds of SIDCs, of tens of terabytes each. In its first year the SKA Phase 1 is expected to collect over 8 EB of data. The data volumes for the full SKA are expected to be by at least an order of magnitude larger.

Even taking into account projected advances in HDD/SSD and network technologies, such large SIDCs cannot be processed or stored on local user computers. Most of the imaging data will be never seen by a human, but rather processed automatically (Whiting, 2012; Popping et al., 2012; Jurek and Brown, 2012; Whiting and Humphreys, 2012). However, there will still be a number of cases where visualisation is going to be required, e.g. data quality control/assessment or detailed studies of individual objects.

Visual exploration of such large data volumes requires a new paradigm for the generation and servicing of the higher level data products to the end-user. In this paper we present a straw man of the functionality required to enable working with extremely large radio astronomy imagery. We consider the JPEG2000 industry standard as a suitable example that addresses many similar requirements, even though it was originally developed for medical and remote sensing imagery.

Currently, most radio astronomy imaging data is stored and distributed in one of three formats: FITS (Flexible Image Transport System) (Pence et al., 2010); CASA Image Tables1 and newly developed by LOFAR HDF5-based format (Anderson et al., 2011). FITS and HDF5 are, in general, single self-describing files containing the image data, as well as metadata. CASA, on the other hand, uses a different approach representing any data as a hierarchical structure of directories and files. CASA data is usually distributed as an archived file created by using common archiving software, such as tar.2 These formats provide both, portability and access to image data. Currently, image files or CASA tar-balls are normally retrieved from an archive and stored on a local computer for exploration, analysis or processing purposes. Alternatively, a specified part of an image-cube (cutout) is produced in one of the image formats, and presented to the user as a download. If coterminal regions are required, several cutout files would be produced and downloaded. The example of such a framework is Simple Image Access Protocol

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1 http://asci.net/1107.013.
2 http://en.wikipedia.org/wiki/Tar computing/.
(SIAP)\textsuperscript{3} of the International Virtual Observatory Alliance (IVOA)\textsuperscript{4} that provides a uniform interface for retrieving image data from a variety of astronomical image repositories. By using SIAP the user can query compliant archives in a standardised manner and retrieve image files in one or more formats, depending on the archive capabilities (e.g. FITS, PNG or JPEG). The resulting files can then be stored on a local computer or a virtual network storage device that is provided through VOSpace, which is another IVOA standard.

In the paper we discuss the use case of extremely large SIDs in the context of the limitations of the current standard astronomy file formats. We present the analysis of the applicability of the approach taken in developing JPEG2000 standards to addressing the new requirements of extremely large astronomical imagery. We also present some interesting benchmarks from using JPEG2000 on large radio astronomy images.

The rest of this paper is structured as follows. In Section 2, we discuss the specific requirements of extremely large imaging. Section 3 discusses JPEG2000 standards, and how they have addressed the requirements of extremely large imaging. We specifically discuss the image interaction protocol in detail as the alternative to the one used in astronomy cutout framework. Section 4 presents benchmarks for JPEG2000 compression for radio astronomy images. In Section 5 we discuss the strategic approaches for improving the existing astronomy standards or the adoption of new industry standards. Finally, we conclude in Section 6.

### 2. Use case for extremely large images

**ASKAP Science Data Archive: Requirements and Use Cases**\textsuperscript{5} indicate the individual data product sizes up to 2.24 TB for some science cases at the maximum interferometer baseline 6 km. By 2020 ASKAP will be incorporated into the SKA1-Survey increasing the number of antennas from 36 to 96 and the maximum baseline to 50 km. The individual data products can be expected as large as 32 TB.

Fig. 1 shows the capacity of HDD over the years. The projection assumes the currently observed average growth of disc capacity at 32% rate. The disc capacity increases by factor of 20 every 10 years. If the same rate is sustained, by the time SKA1 is constructed (2020–2023), the individual disc capacity can be expected to be about 32 TB.

Fig. 2 shows the maximum sustained bandwidth of HHDs over the years (Freitas et al., 2011). One can see that the improvement rate is rather moderate, about 4–5 times per decade. Fig. 3 shows the increasing read time of the entire HDD over the years.

Of course, such a read only indicates the time needed to read the data sequentially. In many cases, during the scientific data analysis, the data is accessed randomly. Being a mechanical device, HDD requires a time to relocate the head to the required position, and wait until the disc turns into the right position before the needed data can be accessed. This delay translates into a latency when the data need to be accessed randomly. Fig. 4 shows the average seek time trend in HDD over the years. The improvement is very moderate, factor about 1.7 per decade.

Solid State Drives (SSD) is a promising technology that may help to overcome the I/O bandwidth and latency problems in the future, though, at the time of writing this paper, the market only offers 1 TB SSD for the desktop/laptop computers, while the largest HDD is 6 TB.

These all means that working with the increasing in size datasets is likely going to be increasingly difficult on personal computers if feasible at all. The software technologies allowing an interactive work with the data stored on a server that can provide a fast parallel access to the data are going to be important for the projects like SKA.

In many cases, images are not required at their full resolution or fidelity. It should be possible to access images at any of a multitude of reduced resolutions and/or reduced fidelities, according to need, all from a single master image. Such a multi-resolution representation should not lead to increased storage requirements, which are already high. For example, pyramid representations (Adelson et al., 1984) possess the desired multi-resolution accessibility attributes, but inevitably expands the data.
We also note that not all of the image might be required at the same level of quality. Particular regions of interest (ROI), e.g. containing an object to be studied, such as a galaxy or a nebula, may need to be of much higher quality or resolution than others. Producing a cutout or many cutouts is a limited solution, as cutouts completely remove the surrounding area. This is problematic because the surrounding area provides context for reconstructing the relationship between multiple objects in the field of view; moreover, the imagery within the surrounding area may be of interest in its own right. A much better approach, in this case, would be to have an adaptively encoded image, in which the regions of interest are encoded with higher fidelity/resolution than the surrounding areas.

Even combining such advanced techniques as multiple resolution/fidelity and adaptive encoding/transfering of ROI, the images can still be very large and require time to be transferred to the client. In the case of the visual exploration of data, it would make sense to immediately transfer only the data that is required for display. Other parts of an image could be requested and transferred on demand. The protocol should be intelligent enough for such a use case.

It would also be very useful to support the progressive transfer of an image from a server to the client. That is, the user should be able to see the whole image of the selected region queried as soon as a cutout portion of the data is transferred, while each successive portion of the data that is transferred should serve to improve the quality of the displayed imagery. By contrast, many “pyramid” techniques possess only multi-resolution access, without progressive transfer, so that higher quality representations must completely replace the lower quality ones, leading to substantial inefficiencies and much higher transfer bandwidths. The client-server framework should be intelligent enough not to transfer more data than is necessary for displaying or processing the content that is of interest.

Further, we will demonstrate that radio astronomy imaging data can be effectively compressed, and the error due to the compression can be controlled. Compression significantly reduces the cost of storage, operations and network bandwidth. However, it should be possible to access image regions, resolutions and qualities directly from the compressed representation. If the imagery must first be decompressed, and then re-compressed to address a user’s needs, this will place unreasonable computational and memory demands upon the server, leading to a large latency in service time and limited ability to serve a variety of users. Ideally, decompression should occur only at the point where an image is to be displayed or used. Some usage cases can expect large ratios in compression; examples include visual data exploration, draft mosaicking, etc. Other use cases may be less tolerant to the loss of fidelity in the data, e.g. source finding. It follows that multiple levels of compression should be available:

- high fidelity, potentially even numerically lossless compression, in which the decompressed image is either an exact reproduction of the original uncompressed image, or differs by considerably less than the intrinsic uncertainties in the imaging process; and
- lossy compression, where the decompressed image exhibits higher levels of distortion that are considered acceptable in exchange for corresponding reductions in communication bandwidth or storage requirements.

As is suggested by the last point above, distortion metrics need to be defined and made available to a user, so that the impact of lossy compression can be controlled. Such metrics involve:

- statistical characterisation of how the decompressed image can be expected to differ from the original image; and
- measures of the impact that different levels of distortion can be expected to have on some specific purposes of data exploration, e.g. source finding.

The second point is especially important, given that much of the new Radio Astronomy science is done at a very low signal-to-noise ratio (SNR).

3. Case study: JPEG2000

In developing a contemporary protocol for working with extremely large astronomical images it is useful to study how other communities have approached this problem. Indeed, large images are not unique to astronomy, though new telescopes such as the SKA will be at the very extreme end of the spectrum. Medical imaging, remote sensing, geographic information systems, virtual microscopy, high definition video and other applications have long histories of development in the imaging domain. The large size of images is not the only similarity. Multi-frequency, multi-component, volumetric datasets, and metadata are common attributes in a range of existing imaging fields. A number of advanced image/metadata formats and access layer protocols have been developed over the years. Some of the formats use wavelet encoding that enables not only efficient compression but also advanced options for interaction with the image data (e.g. MrSID\(^7\), JPEG2000\(^8\), or ECW\(^9\)).

One of those, namely JPEG2000, has been developed into a comprehensive royalty free industry standard—ISO/IEC 15444. Due to the specific focus of the standard on the large imagery, instead of the consumer photography, the standard has become widely adopted by the industries, such as medical imaging (Anastassopoulos et al., 2002), meteorology and remote sensing (Kosheleva et al., 2003), Sun (Muller et al., 2009) and planetary imaging (Powell et al., 2010), and microscopy (Germán et al., 2014). We believe that the astronomy community may benefit from this development, and learn from those industries that had faced similar challenges before astronomy.

JPEG2000 is an image compression standard and coding system created by the Joint Photographic Experts Group committee and published as the international standard JPEG2000 (Taubman and Marcellin, 2002) in 2000. The standard was developed to address weaknesses in existing image compression standards and provide new features, specifically addressing the issue of working with large images. Considerable effort has been made to ensure

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6 http://en.wikipedia.org/wiki/Comparison_of_graphics_file_formats.
7 http://en.wikipedia.org/wiki/MrSID.
8 http://www.jpeg.org/jpeg2000/.
9 http://en.wikipedia.org/wiki/ECW_(file_format).
that the JPEG2000 codec can be implemented free of royalties. Today, there is a growing level of support for the JPEG2000 standard, through both proprietary and open source software libraries such as: OpenJPEG,10 JasPer (Adams and Kossentini, 2000), Aware.11 JPEG2000 has been successfully used in a number of astronomy applications already, including the HiRISE (high resolution Mars imaging) project (Powell et al., 2010) and JHelioviewer (high resolution Sun images) (Muller et al., 2009).

The following key objectives were considered during the development of the standard. It was expected to allow efficient lossy and lossless compression within a single unified coding framework as well as to provide superior image quality, both objectively and subjectively, at high and low bit rates. It was expected to support additional features such as: ROI coding, a more flexible file format, and, at the same time, to avoid excessive computational and memory complexity, and excessive need for bandwidth to view an image remotely.

The main advantage offered by the approach used in JPEG2000 is the significant flexibility of its codestream. The codestream obtained after compression of an image with JPEG2000 is scalable, meaning that it can be decoded in a number of different ways. For instance, by truncating the codestream at any point, a lower resolution or signal-to-noise ratio representation of the image can be attained; moreover, the truncated representation remains efficient, in terms of the tradeoff that it represents between fidelity and compressed size. By ordering the codestream in various ways, applications can exploit this so-called “scalability” attribute to achieve significant performance benefits (Taubman and Marcellin, 2002).

The following main features of JPEG2000 make it an attractive approach for astronomy:

- High compression performance, substantially superior to JPEG.
- Availability of multi-component transforms, including arbitrary inter-component wavelet transforms and arbitrary linear transforms (e.g., KLT, block-wise KLT, etc.), with both reversible and irreversible versions.
- Multiple resolution representation.
- Progressive transmission (or recovery) by fidelity or resolution, or both.
- Lossless and lossy compression in a single compression architecture. Lossless compression is provided by the use of a reversible integer wavelet transform and progressive transmission of a lossless representation provides lossy to lossless refinement.
- Random codestream access and processing, also identified as ROI: JPEG2000 codestreams, offer several mechanisms to support spatial random access to regions of interest, at varying degrees of granularity. These allow different parts of the same picture to be stored and/or retrieved at different quality levels.
- Error resilience—JPEG2000 is robust to bit errors introduced by communication channels, due to the coding of data in relatively small independent blocks within the transform domain.
- Flexible file format—The JPX file format, in particular, allows for rich and flexible description and composition of components. It allows images to be composed from any number of independently compressed codestreams.
- Extensive metadata support and handling.
- Support for volumetric image cubes, either through the specific set of extensions in Part 10 (a.k.a. “JP3D”) or by using the extensive set of multi-component transforms provided with Part 2 of the standard.
- Interactivity in networked applications, as developed in the JPEG2000 Part 9 JPIP protocol.

3.1. Encoding/decoding

Unlike the binary compression available through cfitsio or HDF5, JPEG2000 is a true image compression that takes advantage of the multidimensionality of data. Fig. 5 depicts the stages of encoding in JPEG2000.

In the first stage, pre-processing is performed. Pre-processing actually contains three sub-stages: Tiling, Level Offset, Reversible/Irreversible Color Transform. This stage prepares the data to correctly perform the Wavelet Transform. During the Wavelet Transform, image components are passed recursively through the low pass and high pass Wavelet filters. This enables an intra-component decorrelation that concentrates the image information in a small and very localised area. It enables the multi-resolution image representation. The result is that 4 sub-bands with the upper left one LL on Fig. 5 containing all low frequencies (low resolution image), HL containing vertical high frequencies, LH containing horizontal high frequencies, and HH containing diagonal high frequencies. Successive decompositions are applied on the low frequencies LL recursively as many times as desired.

By itself the Wavelet Transform does not compress the image data; it restructures the image information so that it is easier to compress. Once the Discrete Wavelet Transform (DWT) has been applied, the output is quantified in Quantisation unit.

Before coding is performed, the sub-bands of each tile are further partitioned into small code-blocks (e.g. 64 × 64 or 32 × 32 samples) such that code blocks from a sub-band have the same size. Code-blocks are used to permit a flexible bit stream organisation.

The quantised data is then encoded in the Entropy Coding unit. The Entropy Coding unit is composed of a Coefficient Bit Modeller and the Arithmetic Coder itself. The Arithmetic Coder removes the
redundancy in the encoding of the data. It assigns short code-words to the more probable events and longer code-words to the less probable ones. The Bit Modeller estimates the probability of each possible event at each point in the coding stream. At the same time as embedded block coding is being performed, the resulting bit streams for each code-block are organised into quality layers. A quality layer is a collection of some consecutive bit-plane coding passes from all code-blocks in all sub-bands and all components, or simply stated, from each tile. Each code-block can contribute an arbitrary number of bit-plane coding passes to a layer, but not all coding passes must be assigned to a quality layer. Every additional layer successively increases the image quality.

Once the image has been compressed, the compressed blocks are passed over to the Rate Control unit that determines the extent to which each block’s embedded bit stream should be truncated in order to achieve the target bit rate. The ideal truncation strategy is one that minimises distortion while still reaching the target bit-rate.

In Data Ordering unit, the compressed data from the bit-plane coding passes are first separated into packets. One packet is generated for each precinct in a tile. A precinct is essentially a grouping of code blocks within a resolution level. Then, the packets are multiplexed together in an ordered manner to form one code-stream. There are five built-in ways to order the packets, called progressions, where position refers to the precinct number:

- **Quality**: layer, resolution, component, position
- **Resolution 1**: resolution, layer, component, position
- **Resolution 2**: resolution, position, component, layer
- **Position**: position, component, resolution, layer
- **Component**: component, position, resolution, layer.

The decoder basically performs the opposite operations of the encoder.

The details and mathematics of JPEG2000 encoding can be found in Gray (2003), Adams (2001), or Li (2003).

### 3.2. File format and metadata

The JPEG2000 file format is organised as a sequence of “boxes”, as depicted in Fig. 6. Boxes play a role in the file format similar to that of marker segments in the code-stream syntax, and they appear consecutively in the file.

There are four required boxes: JPEG2000 Signature, File Type, JP2 Header, and Contiguous Code-Stream boxes.

**IPR**, **XML**, **UUID**, and **UUID Info** boxes are all optional and may appear in any order, anywhere after the **File Type** box. There may be multiple instances of these three boxes.

The JPEG2000 Signature box identifies the file as belonging to the JPEG2000 family of formats. The **File Type** box identifies the file specifically as a JP2 file. The **JP2 Header** box contains information such as image size, bit-depth, resolution, and colour space. The Contiguous Code-Stream box contains a single valid JPEG2000 code-stream. **IPR** contains Intellectual Property Rights information. **XML** boxes provide for the inclusion of additional structured information, while **UUID** and **UUID Info** boxes provide a mechanism for defining vendor specific extensions.

Each of the boxes has an internal structure and sub-boxes containing the information about the image. The details can be found in e.g. Taubman and Marcellin (2002).

The XML box may contain any information whatsoever, provided that it complies to the XML (extensible Markup Language). For example, the discussed later SkyView software uses XML box to contain FITS header “as is” wrapped in a simple XML envelop. Alternatively, one of the IVOA’s data models or some proprietary custom information could be placed in a single or multiple XML boxes.

The **JPX** file format provides even more advanced metadata handling (ISO/IEC, 2004).

![Fig. 6. JP2 file format structure. Rounded corners indicate optional boxes.](image-url)

### 3.3. JPIP

JPIP protocol deserves a special consideration as it offers significantly richer functionality compared to IVOA SIAP.

**JPIP** (JPEG2000 Interactive Protocol) is a client/server communication protocol that enables a server to transmit only those portions of a JPEG2000 image that are applicable to the client’s immediate needs. However, this is achieved in a different way compared to a traditional cutout service, such as IVOA SIAPI. Using an HTTP-based query syntax, together with TCP or UDP based transport protocols, JPIP enables the client to selectively access content of interest from the image file, including metadata of interest. This capability results in a vast improvement in bandwidth efficiency and speed when performing some very important and valuable image viewing tasks in a client/server environment, while reducing the storage and processing requirements of the client. The large images — and the more constrained the bandwidth between client and server — the greater are the benefits brought by JPIP.

JPIP clients access imagery on the basis of a so-called “Window of Interest” (WOI). The WOI consists of a spatial region, at a given resolution, within one or more image components in one or more underlying compressed codestreams, optionally limited to a desired quality level or amount of communicated data. In advanced applications, the WOI may also be expressed relative to one or more higher level composited representations whose definition depends on metadata. JPEG2000 enables the efficient identification and extraction of elements from the compressed codestream(s) that intersect with the WOI. This means that from a single compressed image, a user can remotely extract a particular region of the image, a larger or smaller version of the image, a higher or lower quality version of the image, or any combination of these. JPIP can be used to progressively forward images of increasing quality, giving the client a view of the image as quickly as possible, which improves as rapidly as possible, along the direction of interest.

Such features are most desirable for extremely large radio astronomy images, which can hardly be used without examining

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12 [http://www.ivoa.net/documents/latest/SIA.html](http://www.ivoa.net/documents/latest/SIA.html).
the metadata and previewing the image at low resolution first, transferring only the selected parts of the image to a user's computer. This would normally require generating low resolution images, thumbnails and metadata and linking them all together in a database. In a system equipped with JPEG2000 and JPIP, however, it is only necessary to store a single file per image; lower resolutions and thumbnails can be extracted directly out of this high-resolution JPEG2000 "master" image and streamed or downloaded to the client. This removes the need to store, manage, and link images of different resolutions in the database, which can be cumbersome.

In a typical application, when the user chooses to view a particular image, only the resolution layer required to view the entire image on the screen need to be transferred at first. Quality layers are downloaded progressively to give the user an image as quickly as possible. When the user zooms into a particular region of interest in the image, only that portion of the image is transferred by the server, and only at the resolution that is of interest. Again, the image can be transferred progressively by quality layers. The user can continue to zoom into the image until the maximum quality/resolution is reached, and pan across the image; each time, transferred content is limited to the area of the image being viewed. An interactive user might then scan across different images of a series, maintaining the same region and resolution of interest. Again, only the relevant content is actually transferred. The result is a dramatic increase in speed of viewing, and significant increase in the quality and efficiency of the viewing experience.

3.4. JPIP stream type

The JPIP allows three different types of image data to be transmitted between the server and client: (1) full, self-contained compressed images (typically, but not necessarily, in the JPEG2000 format); (2) tile data; and (3) precinct data (Taubman and Prandoni, 2003).

Full JPEG2000 Images. For this data type the server sends the client complete JPEG2000 images, at the requested resolution. The resolution level is selected to fit in the display window. Because the JPEG2000 images are self-contained, they do not require any additional metadata or headers during transmission; the images are simply sent to the client and the client decodes them.

Tiles. Tiles are rectangular spatial regions within an image that are independently encoded. It can be useful to encode a large image as multiple independent tiles, but even huge images can be encoded as a single tile. A tile-based JPIP service is useful where numerous small tiles have been used during the encoding process; this allows the server to send only the relevant tiles to the client, for decoding. Because tile data is not a self-contained image, additional JPIP messaging headers are attached to convey to the client the contents of the messages. Tiling has been used in a number of image formats (e.g. TIFF). It has been introduced in FITS along with the compression applied to the tiles rather than to the entire image (Pence et al., 2010). However, the use of small tiles reduces compression efficiency and can have a large adverse effect upon the service of reduced resolution imagery, since the effective size of the tiles within reduced resolutions can become very small. In JPEG2000 tiles are not considered as a preferred method of structuring an image, as precincts offer more advanced solution.

Precincts. Precincts are fundamental spatial groupings within a JPEG2000 codestream. Unlike tiles, which represent independently coded regions in space, precincts are defined in the wavelet transform domain. The detail subbands at each resolution level are partitioned into independently coded blocks, which are assembled into precincts. Each precinct represents a limited spatial region within the detail bands that are used to augment the displayed imagery from a given resolution to the next. Since precincts are defined in the transform domain, their contributions to the reconstructed imagery are overlapping. This means that a server which sends the precincts that are relevant to a particular WOI is also sending some content that belongs to surrounding regions, whose extent is resolution dependent. Precincts are the providers of ROI functionality in JPEG2000. The content of a precinct can be sent progressively, so as to incrementally refine the quality of the associated imagery. Additional JPIP messaging headers are attached to the precinct data to convey to the client their contents. This image type is often the most efficient, as it requires the smallest amount of data to be transmitted; moreover, it is equally efficient at all spatial resolutions, unlike tiles, whose size can be optimised only for at a pre-determined resolution. An interesting potential mechanism for exploiting precincts within ASKAP and SKA applications, would be to use source finding algorithms to automatically generate a catalogue of the most relevant precincts, as part of the telescope pipeline. This would enable the selective storage of precinct data based on relevance (from lossy up to potentially numerically lossless), as well as the selective delivery of those precincts to a JPIP client; "empty" parts of an image can be sent at much lower quality or resolution, saving the bandwidth, storage/archive space, and increasing the speed of fetching and viewing the data.

3.5. JPIP operation and features

The client application generates and sends to the server a properly formatted JPIP WOI request, containing information about the specific region of the image that the user wishes to view, along with the desired resolution, image components of interest and optionally explicit quality constraints—alternatively, the client may request everything and expect to receive a response with progressively increasing quality. The JPIP server parses the request, calls the JPEG2000 library to extract the relevant image data, and sends back to the client a formatted JPIP response. When the response data is received, the JPIP client extracts the codestream elements and inserts them into a sparse local cache, from which the imagery of interest is decompressed, rendered and/or further processed on demand. Importantly, JPEG2000 codestreams have such a high degree of scalability that any image region of interest can be successfully decoded from almost any subset of the original content on the server, albeit at a potentially reduced quality. This means that decompression and rendering/processing from a local JPIP cache is an asynchronous activity that depends only loosely on the arrival of suitable data from the server. To the extent that such data becomes available, the quality of the rendered/processed result improves.

Tiles and precinct "databins" are the basic elements of a JPEG2000 image used by JPIP. JPEG2000 files can be disassembled into individual finer elements, called databins, and then reassembled. Each databin is uniquely identified and has a unique place within a JPEG2000 file. Full or partial databins are transmitted from the server to the client in response to a JPIP request. The JPIP client can decode these databins and generate a partial image for display at any point while still receiving data from the server.

JPIP provides a structure and syntax for caching of databins at the client, and for communication of the contents of this cache between the client and the server. A client may wish to transmit a summary of the contents of its cache to the server with every request, or allow the server to maintain its own model of the client cache by maintaining a stateful session. In either case, a well-behaved server should reduce the amount of data it is transmitting in response to a JPIP request by eliminating the databins that the client has already received in previous transmissions. In this way, JPIP provides a very efficient means for browsing large images in a standards-compliant fashion.

Both precinct and tile databins have the property that they may be incrementally communicated, so that the quality of the associated imagery improves progressively. JPIP also provides for the
partitioning of metadata into databases, which can also be communicated incrementally. This allows large metadata repositories to be organised and delivered on demand, rather than as monolithic datasets. Moreover, metadata can be used to interpret imagery requests and the image WOI can also be used to implicitly identify the metadata that is of interest in response to a JPIP request.

While databases are being transferred between the server and the client, they usually get split up into smaller chunks, called messages. The JPIP server decides the JPIP message size. This flexibility to transmit partial databases enables one to vary the progressive nature of the data being sent to the client. If entire databases are sent, first for the lower resolution levels in the codestream and then for the higher resolution levels, the imagery pertaining to the requested WOI will be received in a resolution-progressive fashion; if messages from different databases at the same resolution level are interlaced, the data will be received by the client in a quality-progressive order. This flexibility allows applications to control the user experience, depending on the application requirements (Taubman and Prandolini, 2003).

There are numerous implementations of JPIP servers and client SDK available: OpenJPEG JPIP,\(^{13}\) LEADTOOLS,\(^{14}\) KDU SDK from Kakadu Software,\(^{15}\) 2KAN,\(^{16}\) JPPiPK as part of Geospatial Data Abstraction Library,\(^{17}\) and other.

4. Benchmarking of JPEG2000 compression on radio astronomy images

As yet, JPEG2000 has not been used in astronomy very widely. Most of the accessible radio astronomy images are stored in FITS or CASA Image Tables. At the time when this investigation started there was no software available to convert FITS or CASA Image Tables to JPEG2000 images with a sufficient range of encoding parameters. To begin with, we limited ourselves to encoding FITS images only, as the most common image format currently used in astronomy.

4.1. Software

\(\text{f2j}\) software was developed to convert FITS files to JPEG2000 images. The software has been written in C using the open source OpenJPEG\(^{18}\) codec version 1.0.\(^{19}\) for JPEG2000 compression and NASA’s cfitsio (ascl:1010.001) library for reading FITS files.\(^{20}\) \(\text{f2j}\) is an open source software, and can be downloaded from the Github.\(^{21}\)

\(\text{f2j}\) encodes FITS files as JPEG2000 images with a single component consisting of greyscale pixel intensities stored as 16 bit unsigned integers. Each plane of a data cube is written to a separate JPEG2000 image. \(\text{f2j}\) reads a full plane from a FITS file into an array and then processes each raw value in this array into a greyscale pixel intensity. This results in, what is essentially, a bitmap image being passed to the JPEG2000 encoder.

There are multiple options as to how raw FITS data may be transformed into pixel intensities. The particular transformation applied depends on the data type used to store the raw FITS values. In the case of 8 or 16 bit integer data, raw values may be used directly as pixel intensities. At the time of the first trials OpenJPEG v1.0 codec did not support floating point data directly, so floating point values had to be converted to integers in order to create a JPEG2000 image from such data. Later releases of OpenJPEG, however, already support a full range of data types that includes double and single precision floating point.

Arbitrary transformations may be defined in \(\text{f2j}\) for this purpose and it is relatively easy to add new transformations to the program. The floating point transformations currently implemented work by assigning the smallest and largest raw data values in the FITS file to the lowest and highest possible pixel intensities respectively and then scaling the intermediate data in various ways. The logarithmic, square root and power scales are available.

The JPEG2000 standard specifies that image components may be represented with arbitrary precisions up to 38 bits (Schelkens et al., 2009), however OpenJPEG stores pixel intensities using 32 bit integers (in the internal structure it uses to represent an image prior to passing it to the JPEG2000 encoder), limiting the precision attainable. Through experimentation it was also determined that OpenJPEG could not correctly encode and decode images using 32 bit precision due to an error in the library. However, the used images had the dynamic range that could be mostly sufficiently accurately represented by 16 bit precision.

In the case of floating point data, it was observed that files would often use only a tiny portion of the full range of values supported by this data type. As the data is scaled to the minimum and maximum of the allowable 16 bit integer range, the small range of values being scaled would lessen the loss of precision as a result of this quantisation.

There are many compression options that may be specified affecting how an image is encoded using JPEG2000, such as the number of resolutions in the file, tile sizes, compression ratios and the use of lossy or lossless compression. \(\text{f2j}\) supports almost all of the compression options supported by OpenJPEG codec v1.0.

As we were interested in testing the quality of JPEG2000 compression on radio astronomy images, as well as converting FITS files to JPEG2000, \(\text{f2j}\) had been equipped with some benchmarking and experimentation features. The software is capable of adding varying amounts of Gaussian noise to an image to investigate the effects of noise on the compression process. It can perform quality benchmarks to examine how lossy compression degrades an image, by decompressing an encoded JPEG2000 image from a file and calculating quality metrics comparing it to the uncompressed image.

While we have acknowledged the usefulness of JPIP protocol, and its ability to significantly extend the cutout method of interrogation of image data, which is currently the mainstream method in astronomy, in all further presented tests in this paper we benchmarked only image files stored on a local drive leaving benchmarking of JPIP for a future investigation.

4.1.1. Metrics

We have built-in \(\text{f2j}\) the options to calculate the mean squared error (MSE), root mean squared error (RMSE), peak signal to noise ratio (PSNR), mean absolute error (MAE), fidelity and maximum absolute distortion (MAD) metrics (as well as intermediate data for these metrics). These metrics are recommended for compression benchmarks (Delcourt et al., 2011).

In practice, we have found the fidelity metric to be unhelpful, as in none of the tests conducted did it drop below 0.98, even for badly distorted images. MSE, RMSE and PSNR are all re-expressions of the same information and thus interchangeable. PSNR was found to be the most intuitive to work with and was therefore used in most of our tests.

\(^{13}\)https://code.google.com/p/openjpeg/wiki/JPIP.

\(^{14}\)http://www.leadtools.com/sdk/jpipj.

\(^{15}\)http://www.kakadusoftware.com.

\(^{16}\)http://www.2kan.org/demonstrator.html.

\(^{17}\)http://www.gdal.org/frmt_jpjpakak.html.

\(^{18}\)http://www.openjpeg.org.

\(^{19}\)v2.0 was already available at the time when the paper was written.

\(^{20}\)\(\text{f2j}\) does not transfer FITS headers to JPEG2000 files, however, the software described in Peters and Kitaeff (2014) does transfer FITS headers into metadata boxes of JPX.

\(^{21}\)https://github.com/ICRAR/f2j.git.

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MAE is not directly related to RMSE, but one would intuitively expect these metrics to be closely correlated. This was verified in practice. Fig. 7 shows the values of MAE collected in quality versus compression ratio benchmark tests (vertical axis) plotted against RMSE values (horizontal axis)—a clear linear relationship is visible. The correlation coefficient between the two variables is 0.992. The close correlation between RMSE and MAE supports the conclusion that MAE offers little information beyond RMSE (and thus PSNR). Thus our discussions of results will focus on PSNR and MAD mostly.

4.1.2. Test images

A large number of publicly available radio astronomy FITS files were examined to come up with a representative set of test images representing features and attributes that radio astronomers would expect to encounter. These include sparsely and densely populated images, dominant and diffuse features, high or low noise and regular or random noise. A final test set of 11 images was selected, including 9 planar images and 2 data cubes. All images contained floating point data. These images were used in the benchmarking described in the following sections.

4.2. Lossless compression benchmarking

These benchmarks involved encoding the test images losslessly and observing the compression ratios attainable.

There are many parameters that might be specified when encoding to a JPEG2000 image. These allow the image compression to be fine-tuned for a particular purpose, i.e. for distribution as part of a JPIP system and have the potential to affect compression ratios and image quality (for lossily encoded images). For the initial benchmarking, other than altering the compression ratios and target quality for the lossy compression benchmarks (below), the default OpenJPEG settings were used as typical parameters. Therefore, while our project provides a guide to the compression performance possible using JPEG2000, best results for any practical application will result from optimising the compression process for a particular use.

Table 1 shows the lossless compression ratio attained for each of the 11 test images, the space saved as a result of compression, and the sizes (in bytes) of the JPEG2000 images and original FITS files.

In terms of lossless compression ratios, there are two obvious outliers in this table: M31_model_5Mpc.fits and CYG.ICLN.FITS. The first is a very clean data cube containing a simulated ASKAP image of the M31 galaxy, which achieved a compression ratio of 1:50.79. The second image is of Cygnus A observed on the EVLA, which achieved a more modest compression ratio of 1:10.01 (see Fig. 8). This image contained a reasonable amount of instrumental noise, but nevertheless this noise could be represented efficiently using the JPEG2000 lossless algorithm.

Not taking in account the outliers, the mean compression ratio was 1:3.89 with a standard deviation of 0.80. Of the remaining images, the worst compression ratio, of 1:2.90, occurred with the file 00015 + 00390Z.fits (see Fig. 9). This was a very noisy (mostly instrumental) image as observed on the VLA array. The worst compression ratio this image was achieved despite the fact that the instrumental noise has a regular but very finely gridded structure.

Of the remaining files, the best compression ratio of 1:5.47 was achieved on the file 1.4516.65_TESTS_1994JUL24_1_120.U2.61M.imfits, which contained a relatively clean image of RC2357 as observed from the VLA array (see Fig. 10). The image also has constant values in all four corners that contributes to the high compression ratio.

4.3. Lossy compression benchmarking

4.3.1. Quality versus compression ratio benchmarks

These benchmarks involved compressing the test images lossily by specifying a particular compression ratio to the JPEG2000 encoder. Compression and quality metrics were recorded for each of the compressed images. The compression ratios at which compression artefacts first became visually noticeable (relative to the losslessly compressed version) were recorded. The residual images

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22 http://www.atnf.csiro.au/people/Matthew.Whiting/ASKAPsimulations.php.
23 Credit to Richard Dodson of ICRAR for the original FITS files.
Table 1
Lossless compression benchmarking results. The compression ratios are true ratios for all the images including those that had been truncated from 32 bit to 16 bit integers.

| File Size of JPEG2000 file (bytes) | Size of FITS file (bytes) | Compression ratio | Disk space saved (%) |
|-----------------------------------|---------------------------|-------------------|---------------------|
| 1.45I1.50_AM0381_1992DEC14_1_125.U50.7S.imfits | 110,689 | 406,080 | 1:3.67 | 73 |
| 1.45I4.68_AK456_1998AUG28_1_76.U1U2.95M.imfits | 120,021 | 406,080 | 1:3.38 | 70 |
| 1.45I4.70_AK456_1998SEP04_1_131.U1U6.8M.imfits | 86,841 | 406,080 | 1:4.68 | 79 |
| 1.45I6.65_TESTS_1994JUL24_1_120.U2.61M.imfits | 74,199 | 406,080 | 1:5.47 | 82 |
| 1.45I9.04_AB778_1996JAN29_1_42.6U4.91M.imfits | 103,796 | 406,080 | 1:3.91 | 74 |
| 1.45I10.1_AK456_1998NOV15_1_23.3U4.63M.imfits | 118,756 | 406,080 | 1:3.41 | 71 |

Table 2
Quality benchmarks for lossy compression at the compression ratio of first visual degradation. The compression ratios in the table are those supplied to the JPEG2000 encoder. The numbers in brackets next to the file names indicate a particular plane (frequency channel) of a data cube.

| Compression ratio | File | PSNR (dB) | MAD |
|-------------------|------|-----------|-----|
| 1:15              | 1.45I1.50_AM0381_1992DEC14_1_125.U50.7S.imfits | 46.3 | 2241 |
|                   | 1.45I4.68_AK456_1998AUG28_1_76.U1U2.95M.imfits | 41.4 | 3295 |
|                   | 1.45I10.1_AK456_1998NOV15_1_23.3U4.63M.imfits | 42.0 | 3590 |
|                   | 00015+00390Z.fits | 45.5 | 2031 |
|                   | CYG.ICLN.FITS | 46.3 | 1859 |
|                   | M31_5Mpc_dirty_6km.fits(110) | 49.2 | 3942 |
| 1:20              | 1.45I9.04_AB778_1996JAN29_1_42.6U4.91M.imfits | 46.3 | 1859 |
|                   | M31_5Mpc_dirty_6km.fits(40) | 47.4 | 2621 |
|                   | M31_5Mpc_dirty_6km.fits(75) | 46.4 | 3941 |
| 1:25              | 1.45I4.70_AK456_1998SEP04_1_131.U1U6.8M.imfits | 51.4 | 1760 |
|                   | M31_5Mpc_dirty_6km.fits(5) | 43.4 | 3590 |
|                   | M31_5Mpc_dirty_6km.fits(145) | 43.8 | 3932 |
| 1:30              | 1.45I6.65_TESTS_1994JUL24_1_120.U2.61M.imfits | 54.5 | 1987 |
|                   | 22.4I0.94_AF350_1998DEC24_1_3.41M55.7S.imfits | 48.8 | 3160 |

Table 3
Compression benchmarks at the quality (PSNR) of first visual degradation.

| PSNR (dB) | File | Compression ratio |
|-----------|------|-------------------|
| 50        | 1.45I5.0_AM0381_1992DEC14_1_125.U50.7S.imfits | 1:24 |
|           | 1.45I4.70_AK456_1998SEP04_1_131.U1U6.8M.imfits | 1:62 |
|           | 1.45I6.65_TESTS_1994JUL24_1_120.U2.61M.imfits | 1:80 |
|           | 1.45I9.04_AB778_1996JAN29_1_42.6U4.91M.imfits | 1:32 |
|           | 22.4I0.94_AF350_1998DEC24_1_3.41M55.7S.imfits | 1:58 |
| 40        | 1.45I6.68_AK456_1998AUG28_1_76.U1U2.95M.imfits | 1:41 |
|           | 1.45I10.1_AK456_1998NOV15_1_23.3U4.63M.imfits | 1:36 |
|           | 00015+00390Z.fits | 1:111 |
|           | M31_5Mpc_dirty_6km.fits(5) | 1:102 |

resulting from the lossy compression process were written to files and were visually examined for features of interest.

Compression ratios of 1 : X were used, where X took the values 25, 20, 15, 10, 5, 2, 1.5. Higher compression ratios were examined if there were no visible compression artefacts at the 1:25 compression ratio.

Table 2 shows the nominal compression ratio at which each file first showed visual degradation and quality metrics at this point. Note that the compression ratios in the table are those supplied to the JPEG2000 encoder. The numbers in brackets next to the file names indicate a particular plane (frequency channel) of a data cube.

The first point to note is that every file could be compressed losslessly to a nominal 1:10 ratio without showing visual degradation, which is 2.6 times greater than the average 1:3.89 compression ratio attainable using lossless compression.

Fig. 11 shows the PSNR values recorded at the compression ratios that visual degradation first occurred.

From the graph, it is obvious that while visual degradation first occurred over a relatively narrow PSNR range, it occurred over a relatively wide nominal compression ratio range. This observation motivated the next set of benchmarks.

4.3.2. Compression ratio versus quality benchmarks

These benchmarks investigated the opposite side of the equation to the previous set of benchmarks. The tests proceeded as in the previous section, except that the test images were compressed lossily by specifying a particular target quality, expressed as a peak signal to noise ratio (PSNR), to the JPEG2000 encoder, rather than specifying a compression ratio. For these benchmarks, FITS files were encoded lossily with a particular targeted quality (PSNR). The quality metrics here are thus largely influenced by this compression parameter—therefore it is the compression metrics that are of interest in these tests.

Table 3 shows the compression ratios achieved at the PSNR (quality) that files first showed visual degradation.

Fig. 12 shows the compression ratios attained at the PSNR that visual degradation first occurred. Again, it is obvious that visual degradation first occurs over a relatively wide range of compression ratios but a relatively narrow PSNR range. Thus the target
Fig. 10. RC2357 as observed on the VLA array.

Fig. 11. PSNR at the nominal compression ratio at which visual degradation first occurred.

PSNR appears to predict visual image quality far better than compression ratio. When working with lossily compressed images, it would thus be advisable to encode images for a particular quality using PSNR as a metric rather than a particular compression ratio.

5. Improving existing formats, adopting other technologies or starting from scratch?

5.1. Improving of existing formats

The FITS standard, in its present form, is clearly unable to support such cases as ASKAP or SKA. Can it be improved? White et al. (2012) have made perhaps the most significant attempt to improve FITS for the large images use case. The convention suggests that compressed tiles of image are stored in a binary table extension which is hidden from the end-user as the image is accessed through the same image interface that is used to access normal raw images. However, this convention does not offer any new framework to work with the imagery data. As before, a cutout needs to be produced as a separate file and downloaded to the client. Comparing to the described JPIP client–server framework the cutout framework is clearly limiting for many use cases, especially that involve visualisation.

Another problem for improving existing standards such as FITS, is its expected and important property of backwards compatibility. Such legacy often conflicts with the modern performance and flexibility requirements (Anderson et al., 2011). On the other hand, FITS rather loosely specifies the formats for various uses, and conservatively defines the metadata. As the result, the actual use of FITS often deviates from the original specifications in order to accommodate the specific needs of projects or to extend the functionality in general. This creates an illusion of a standard, while in reality there are many proprietary cases of FITS that software cannot universally interpret.

These are factors, that, in our view, significantly limiting the opportunity to improve FITS in particularly to address large data issue. This looming predicament is especially relevant to such projects as SKA, wherein certain operational modes will be generating datasets comprising tens of terabytes of individual data products.

5.2. Adopting technologies versus starting from scratch

A standard like JPEG2000 requires many years of development by the top experts in the field. The amount of investment in both, time and money required to implement the standard are much greater. Many widely adopted standards are often supported by both commercial and open source developments. The downsides are that not all standards are royalty free to use in development, and that it might be more difficult to influence the development of a standard to accommodate the needs of rather small astronomy community. The industry interest to collaboration in developing standards can be piqued by the high public profile astronomy projects that can be used as a vehicle for promotion of a standard or technology. Projects like SKA may represent the unique opportunities for effective collaboration between the astronomy community and the industry R&D.

Clearly, no single industry standard/technology can address all the needs of astronomy. JPEG2000 is not universal, and only limitedly suitable for handling other types of data e.g. visibilities for radio interferometers. The functionality required for other types of data is significantly different to the functionality required for visual exploration of image data. However, we considered JPEG2000 in detail to demonstrate how powerfully an industry standard can address the requirements for large astronomical imagery. Use of a suitable standard opens access to many tools that are readily available providing a shortcut to the solutions that would take many years to achieve otherwise.

Moreover, we would like to argue that the ability to exchange and correctly interpret the data is more important than: the format of data that needs to be optimised; a particular use case; or an optimisation to a hardware platform. As long as there is a clear description of data in a universal way, the data can be extracted from or ported to any particular format as necessary.

We would like to urge the astronomical community to begin the work of defining the new set of standards to provide a guidance for new developing instruments to efficiently store and exchange the staggering amount of data that are going to be generated in the next decade. The work that has been done by IVOA over the last decade can be a great asset.
6. Conclusion

New telescopes, such as the SKA, will produce images of extreme sizes. Providing adequate performance and level of convenience when serving such images to the end-user is going to be beyond the capabilities of current astronomy image formats. Improvements of the existing image and data formats cannot solve the deficiencies inherently there, due to the fundamental limitations at the time of development.

New advanced technologies are necessary. Technologies such as JPEG2000 have the potential to powerfully pave the way to a contemporary solution that will adequately address the challenges of extremely large imagery.

Substantial reductions in storage/archive requirements can be achieved by losslessly encoding data into JPEG2000 images. Even greater saving may be achieved through lossy compression.

JPIP provides a standard powerful way for interaction with the imagery data reducing the bandwidth, storage, and memory requirements, and increasing the mobility of future astronomy application.

The results of our benchmarks demonstrate the viability of JPEG2000 compression for storing and distributing radio astronomy images. JPEG2000 is not just about compression—it has the potential to enable an entirely new paradigm for working with radio astronomy imagery data.

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