ENSEIRB-MATMECA, Computer Science Department

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What did the X-ray spectrometer of Apollo 15 observe?

Low-level conversion of astronomic binary data

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Foreword and acknowledgements

This report describes the work that I undertook at the European Space Astronomy Center (ESAC, Villanueva de la Cañada, near Madrid, Spain) during a 3-month internship between June and September 2012. This internship is part of my computer science studies at ENSEIRB-MATMECA, Bordeaux, France.

The aim was to decipher and convert the merged binary tape of the X-ray fluorescence spectrometer carried by the Apollo 15 spacecraft during its transearth coast in August 1971.

The story of the American sprint to the Moon 50 years ago have been told and retold many times, and a lot of books analyse it in detail from the first Apollo mission which caused the death of its three astronauts, through the first lunar landing in 1969 and the “successful failure” of Apollo 13, on to the last of six successful Moon landings with Apollo 17 in 1972. All these books are captivating, from a historical point of view as well as from a technical point of view.

I acknowledge all the ESAC staff, contractors, and trainees for their welcoming and for making this 3-month internship a unique instructive and fascinating experience.

I acknowledge David Renault for his advice regarding my work and Yan Sitnikov for correcting this report, in the perspective of the English language, grammar and phrasing.

I acknowledge Aitor Ibarra and Richard Saxton for their help regarding the usage of the SAS.

Finally, I especially acknowledge the assistance of my two supervisors Uwe Lammers and Erik Kuulkers for helping to understand the issues, find solutions, as well as locate original NASA documents, scientific papers and other information, and for checking my work for errors.

Cover image: The Villafranca VIL-2 15m S-band antenna with flags of the 17 member states of ESA. Image ESA - S. Corvaja.

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1 Introduction

1.1 The organization

1.1.1 The European Space Agency (ESA)

ESA allows Europe an access to space since its foundation in 1975. Its mission is to shape the development of Europe's space capability and ensure that European citizens benefit from investments made in space. ESA's missions are designed to find out more about Earth, its space environment, the Solar System and the Universe. ESA also collaborates to other Space Agencies' programs, like these of the National Aeronautics and Space Administration (NASA, Unated States), the Japan Aerospace eXploration Agency (JAXA), the Russian Federal Space Agency (Roscosmos) and other. In 2012, ESA's budget amounted to 4,02 billion euros.

ESA has 18 Member States: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom. Some other countries have a Cooperation Agreement with ESA. These countries finance ESA's programmes and contribute to set ESA's goals.

ESA owns several specialized centers all over Europe:

- **ESTEC** (European Space Research and Technology Centre): base of ESA's science missions in Noordwijk, Netherlands
- **ESRIN** (ESA Centre for Earth Observation): Earth Observation missions in Frascati, Italy
- **ESOC** (European Space Operations Centre): ESA Controls of satellites and spacecrafts in Darmstadt, Germany
- **EAC** (European Astronaut Centre): astronauts training in Cologne, Germany
- **ESAC** (European Space Astronomy Centre), Astronomy and solar system observation, in Villanueva de la Cañada, Spain.

1.1.2 The European Space Astronomy Center (ESAC)

Particularly, the European Space Astronomy Center (ESAC) is located at Villanueva de la Cañada, in the countryside of Madrid, 30 km from the city centre. It is the place from where scientific operations are conducted, and where all of the scientific data produced is analysed, archived and made accessible to the world.

Illustration 1: Aerial view of ESAC

For this purpose, ESAC owns four parabolic antennas: VIL-1, VIL-2, and VIL-4, 12-to-15m antennas located in the ESAC centre itself ; and Cebreros, the ESA's 35m diameter deep-space antenna. These antennas support the activities of ESAC by gathering data from distant missions to Mercury, Venus, Mars, and beyond.

1.1.3 The Science Operation Centers (SOCs) at ESAC

Once a space telescope has reached its operating orbit or final destination, then the Science Operations Centres' task is to ensure that it is used in the best possible way. SOCs' engineers and scientists monitor and control the onboard instruments (cameras and spectrometers). SOCs are responsible for the calibration of the instruments, processing and archiving of the data, and for helping the scientific community to access and understand information coming from the instruments. The SOCs at ESAC are:

- **INTEGRAL**, gamma-ray observatory, launched in 2002
- **XMM-Newton**, X-ray observatory, launched in 1999
- **Mars Express**, dedicated to Mars, launched in 2003
- **Rosetta**, Launched in 2004, it needs ten years to reach its final destination, the comet Churyumov-Gerasimenko.
- **Venus Express**, dedicated to Venus, launched in 2005
- **Herschel**, infra-red observatory, launched in 2009
- **Planck**, studying the relic radiation from the Big Bang, launched in 2009
- **GAIA**, to be launched in 2013, it will produce a 3D-map of the Milky Way

During their traineeship, ESAC trainees also belong to a SOC, depending on the project they are working for. I was integrated in the GAIA team, mainly because my supervisor Uwe Lammers was working on GAIA. However my project had nothing to do with GAIA and has to do with old data coming from Apollo 15.

1.2 The NASA's Apollo 15 mission

1.2.1 Presentation of the mission

Apollo 15 was the ninth manned mission and the fourth lunar landing of the Apollo program, the space program of NASA dedicated to study the Earth's moon. It was carried out in 1971, from the 26th of July, until the 7th of August. Apollo 15 was designed to explore the moon and particularly: explore the Hadley-Apennine region, activate lunar surface scientific experiments, conduct lunar orbital experiments and take photographs. It carried a three-astronauts team: David Scott (born 1932), Alfred Worden (1932) and James Irwin (1930 – 1991).

Like the preceding Apollo missions, Apollo 15 had two main modules:

- The Command/Service Module (CSM) called *Endeavour*: the spacecraft designed to carry the astronauts between Earth and Moon and stay in orbit around the moon. The CSM itself is composed by the Command Module where the crew stayed and the Service Module providing movement and other services.
- The Lunar Excursion Module (LEM or LM) called *Falcon*: the lander portion of the Apollo spacecraft designed to carry two astronauts from the CSM to the surface of the moon

Figure 2 shows the trajectory of both CSM and LEM modules. The trajectory can be split in several main steps:

1) The Earth Orbit Insertion EOI (CSM+LEM)
2) The Trans Lunar Injection TLI (CSM+LEM) during which the SPS was burning to give to the spacecraft a trajectory towards the moon
3) The journey to the moon, called the Translunar coast TLC (CSM+LEM)
4) The Lunar Orbit Insertion LOI (CSM+LEM)
5) 74 orbits around the moon (CSM), while the LEM made a round-trip until the moon
6) The transearth injection TEI during which the SPS was burning to give to the spacecraft a trajectory towards the earth (CSM)
7) The journey to the Earth (CSM), called the Transearth Coast

The orange and red points show respectively of the translunar injection TLI and the lunar orbit insertion LOI.

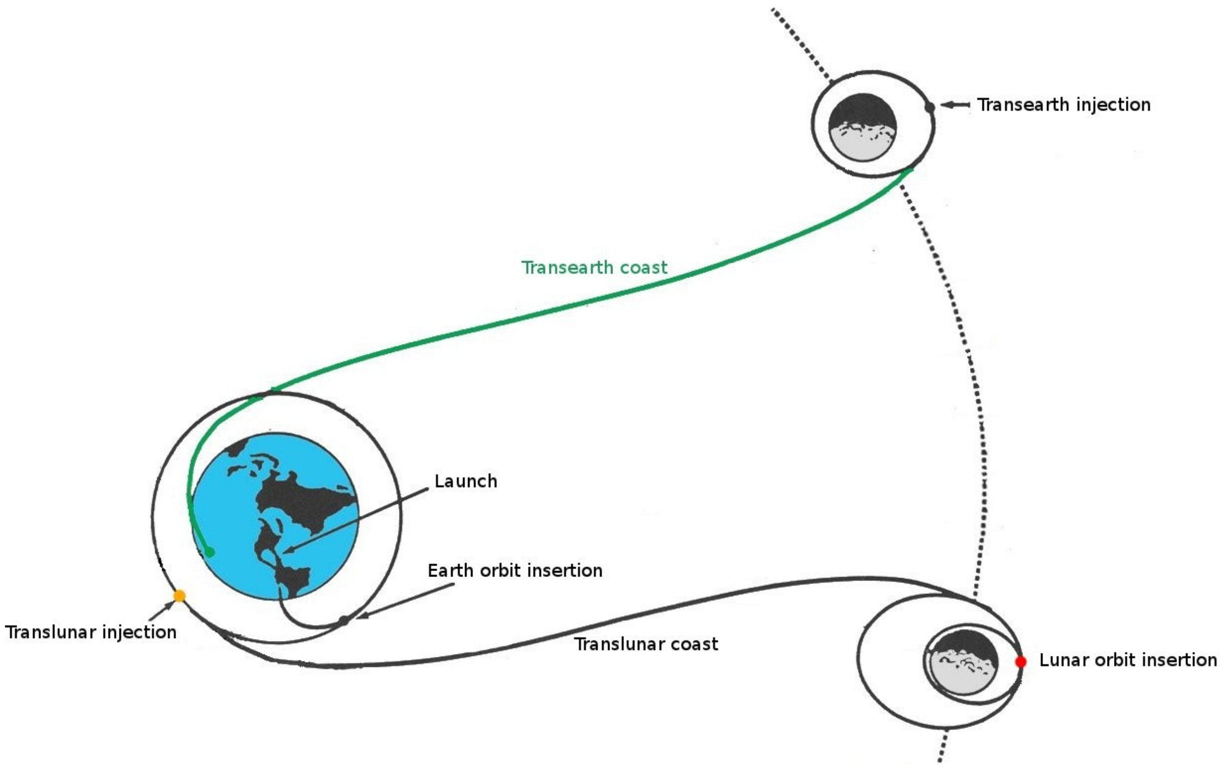


Illustration 2: Trajectory of the Apollo 15 spacecraft

1.2.2 The X-ray Fluorescence Spectrometer

Apart from bringing people to the moon in 1971, Apollo 15 also carried onboard scientific instruments. One of them, the **X-ray Fluorescence Spectrometer**, was mainly used for mapping the lunar surface composition. It was turned on during the lunar orbit and also during the transearth coast. Understanding the nature of these X-ray sources is one of the prime objectives of astrophysics. During the coast, the spacecraft was stabilized seven times to point at seven particular sources during half an hour to an hour.

Physically the spectrometer consisted of 4 detectors counting photons:

- A Beryllium counter
- A Magnesium counter
- An Aluminium counter
- A solar monitor, counting photons coming from the sun

1.2.3 Internship subject

The data taken from the moon from the spectrometer have been analyzed and archived at NSSDC (National Space Science Data Center). To perform their work, an ESA astrophysicist was recently interested in getting access to X-ray count rates coming from different X-ray sources in the sky. Thus they were interested into obtaining the count rates recorded by the Apollo 15 CSM during the transearth coast in 1971.

However, the 40-year-old measurements from the sky up to now were only available in raw format, as a binary file. This kind of raw data was unusable as is. There was some information provided by NASA about how the data was structured in this file, but it was not straightforward enough to decode it. It was necessary to decipher the data, and make it available in a modern format; so that the data could be properly analysed and archived.

Two facts are important to note concerning the X-ray Fluorescence Spectrometer:

- The same experiment has been flown again one year later with Apollo 16
- The recording of X-rays has been conducted while flying over the moon and also during the transearth coast

All this data from the X-ray spectrometer (Apollo 15+16, in orbit and during the transearth coast) are available at NSSDC and come in different formats (binary, ASCII, tables...). Also, a huge amount of documentation came with Apollo 15, Apollo 16, their technical working, their scientific experiments, etc. According to NASA, the data that the ESA scientist was looking for during the transearth coast was only available in a raw binary file. However, other files already deciphered coming from the same instruments and/or during different periods could help to decipher this one.

The aim of the internship was, first, to understand how the binary data was structured into the file and what information was present in it, and second to create a software to convert it into a more readable format. The created software should not be used for any other purpose than this conversion.

2 Working environment

2.1 Astrophysics definitions

2.1.1 Celestial coordinate systems

We call a celestial coordinate system any coordinate system used by astronomers to specify either the position or the direction of a celestial body. Because of the great distances to most celestial objects, astronomers often have little information on their distances, and hence use only the direction. The direction of far objects is the same for all observers and does not depend on their position on Earth.

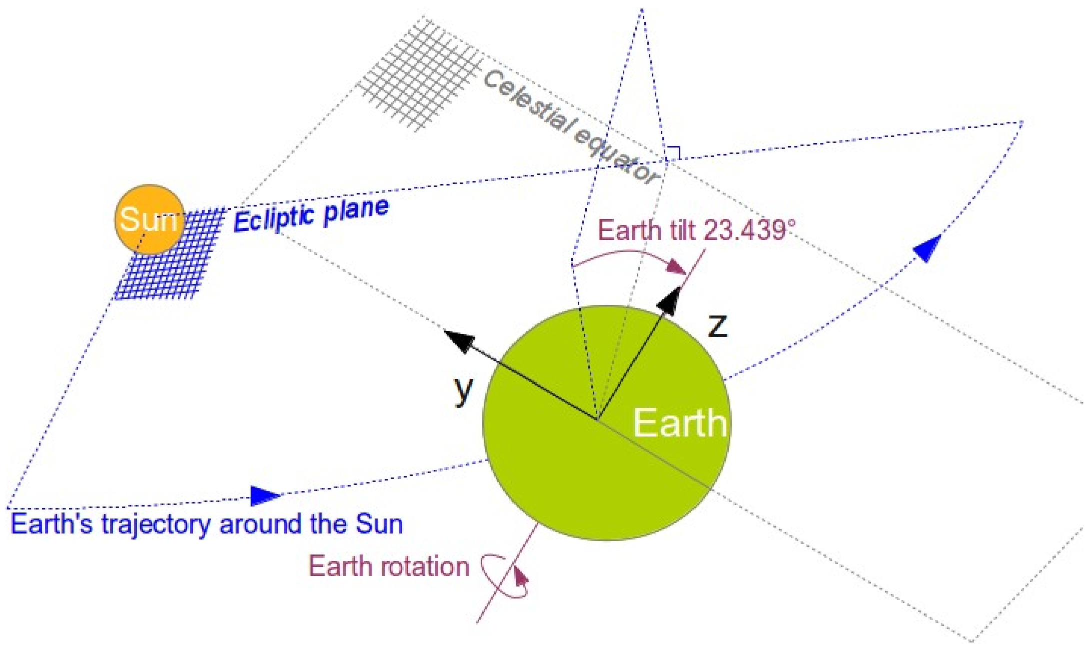


Illustration 3: The Ecliptic and Celestial planes

As showed in illustration 3 the **Ecliptic plane** is the projection of the Earth orbit around the Sun and the **Celestial equator** is the projection of the Earth equator. The Earth rotates around itself around an axis tilted by around 23.439° perpendicular to the Ecliptic plane.

The **equatorial coordinate system** is an Earth-centered celestial coordinate system defining two kinds of equatorial coordinates: Cartesian and Polar.

The Cartesian equatorial system, called ICRF, has the +z axis pointing along the axis of rotation of the earth, the +x axis pointing in the direction of the **vernal equinox**, and the y-axis defined as the cross product of z and x to create a right-handed coordinate system. The x and y axes are on the Celestial equator (illustration 4).

Polar equatorial coordinates can give only the direction of a star instead of its position. The polar coordinate system defines the longitude from the +x axis and the latitude from the celestial equator called respectively right ascension (RA) and declination (Dec). Assuming a given star, its coordinates (RA, Dec) allows to locate it in the sky in term of direction.

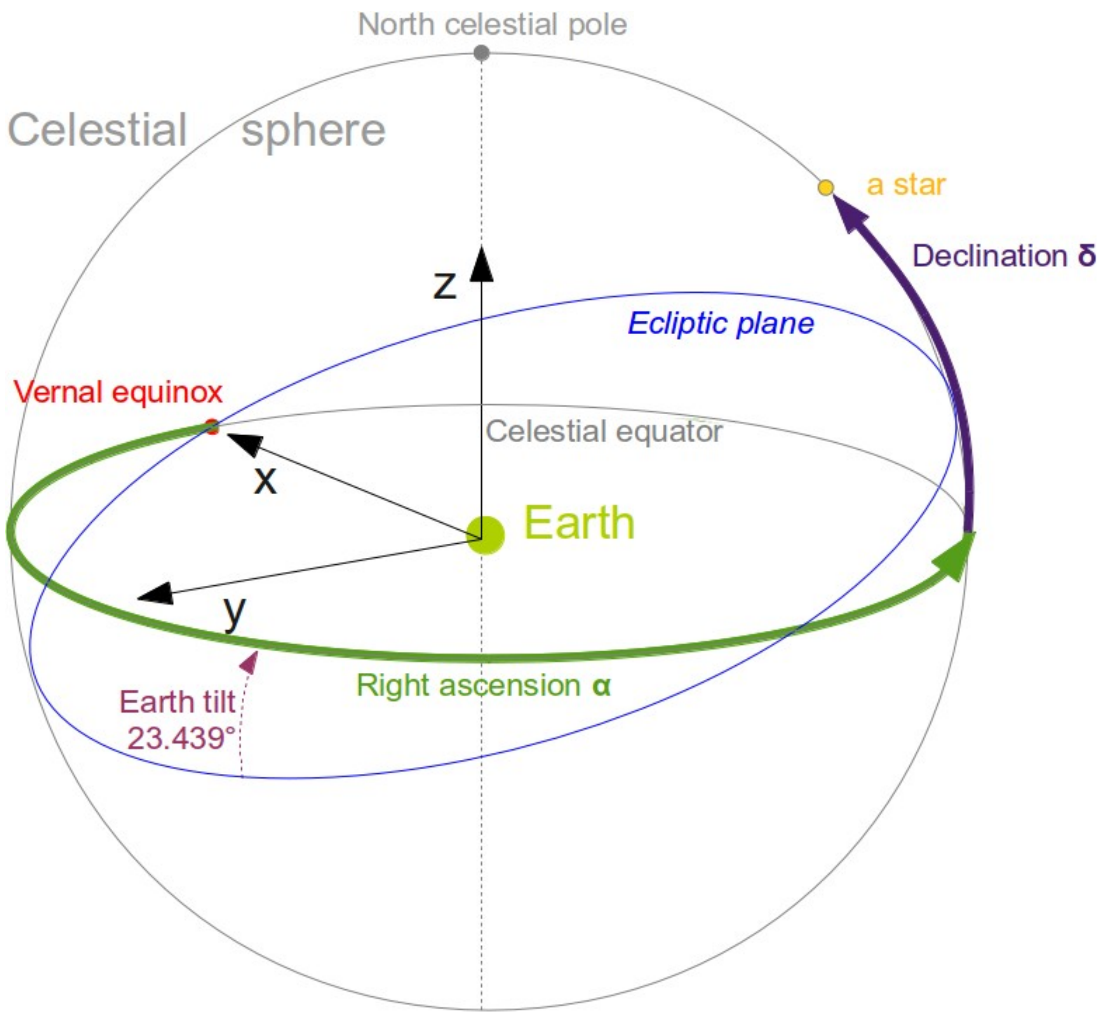


Illustration 4: The equatorial coordinate system (Cartesian and polar)

The right ascension is often measured in hours (24 hours in 360 degrees) from 0^{hr} to 24^{hr}. The declination is often given in degrees from -180° to +180°. For instance Scorpius X-1, a famous X-ray source is located at RA 16h 19m 55.07s, Dec -15° 38' 24.8".

2.1.2 Spacecraft-related time and attitude

Attitude: Roll, pitch, yaw

We call "attitude" related to a spacecraft its orientation relative to the Sun, the Earth or the stars regardless of the distances to these various objects. In practice, and in the case of Apollo 15, the spacecraft's attitude is its orientation related to a reference rotation, in a spacecraft-centered coordinate system. Illustration 5 shows the orientation of the spacecraft regarding the three axes and the definition of the attitude, defined by three rotations around these axes.

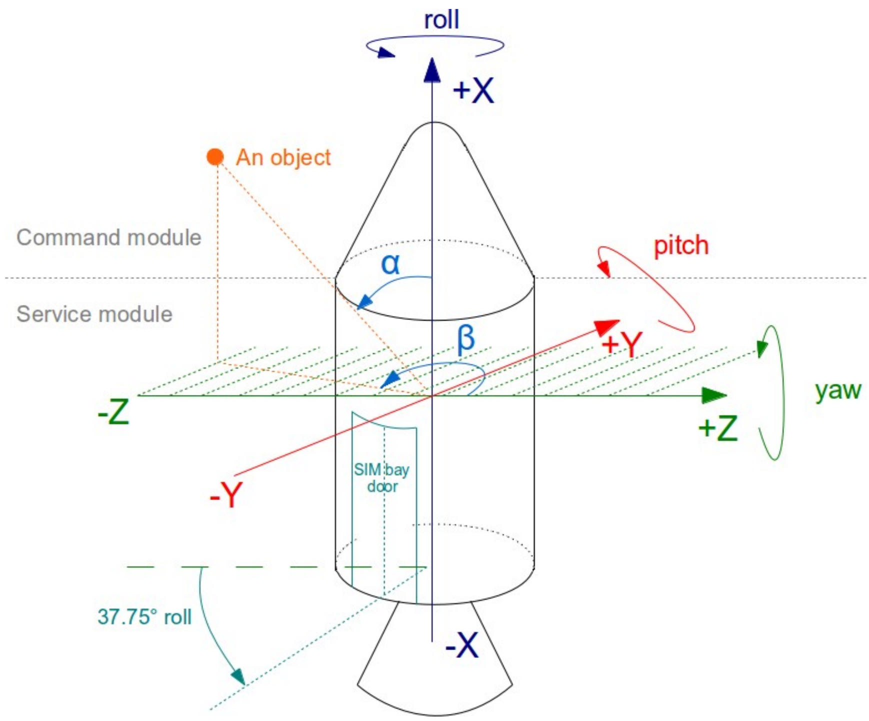


Illustration 5: Body coordinate system of the CSM and the position of the SIM bay

The illustration shows the Body Coordinate System (BCS) of the spacecraft, which takes its origin at the vehicle center of mass, but other coordinate systems were defined, as explained in section 3.3. The α and β look angles are respectively latitude and longitude to locate any object from the point of view of the spacecraft.

Mission time

The time during spatial missions is generally represented in two ways:

- The Ground Elapsed Time: The time elapsed since launch (launch the 26 July 1971 at 16:30 of the Saturn V SA510 in the case of the Apollo 15 spacecraft), e.g. 855,000 s or 238,40 hr.
- The Greenwich Mean Time: The usual date and time at the Greenwich Mean Time, e.g. 4 August 71, 13:42:04

2.2 The Flexible Image Transport System Format (FITS)

2.2.1 Introduction and use

The FITS format, initially introduced by the NASA in 1981, is a file format dedicated to store and manipulate scientific data. It is the data format that is most used in astronomy. It allows to associate some observations (the measurements) and the metadata associated with them (information about the observing satellite, position of the instrument, direction of the observed object, etc...). It is generally admitted that the FITS format is an image format, even though it is a lot more flexible, rich, and can contain binary data, multidimensional arrays, images, arrays of images, etc.

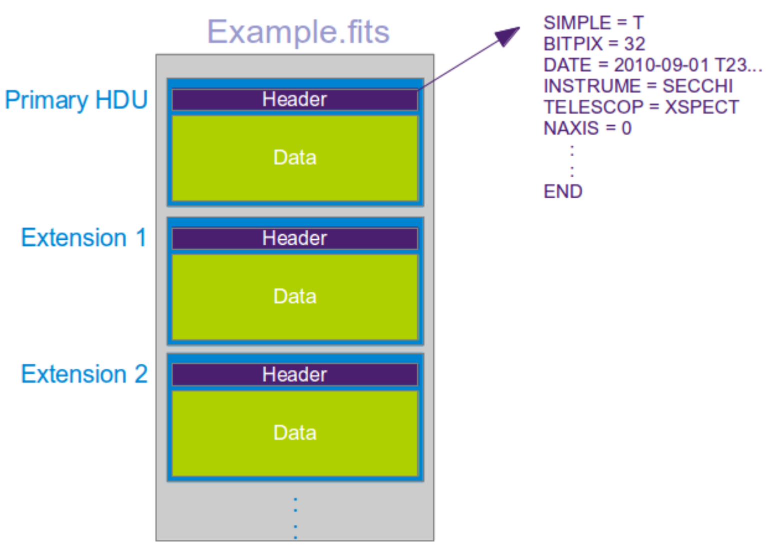
2.2.2 Description of the file format

A data file in FITS format consists of one or more HDUs (Header Data Unit). Each HDU containing two parts: an ASCII header and a binary data block.

The header contains a series of keywords that describe the binary data of the HDU. The header consists of pairs **KEYWORD = value** of 80 characters of maximum length. The keyword is generally capitalized. Some keywords in the primary header are mandatory, others are optional, and custom keywords are allowed. However, the main drawback of custom keywords is that they may not be recognized by all software.

These keywords are mandatory:	Example values (1024x1024 image)
• **SIMPLE** (T if the file is standard, F otherwise)	T
• **BITPIX** (number of data bits per pixel)	32
• **NAXIS** (number of dimensions)	2
• **NAXIS1** (number of elements in dimension 1)	1024
• **NAXIS2** (number of elements in dimension 2)	1024
• **NAXIS3** (number of elements in dimension 3) …	
• **END** (end of the header)	END

Illustration 6: General structure of a FITS file



The first HDU is called the **primary** HDU. The following HDUs are called **extensions**. The general structure of a FITS file is detailed in illustration 6.

The primary HDU must necessarily contain a header and may optionally contain binary data. Extensions can contain different types of data such as ASCII, binary tables, images, ...

Other reserved (but optional) keywords can be added to these mandatory keywords:

- DATE (creation date of the HDU)
- ORIGIN (Source of the HDU)
- EXTEND (are there extensions?)
- DATE-OBS (date of observation)
- TELESCOP, FILENAME, HOW ...

For instance, the data coming from the XMM-Newton satellite are converted in XMM-lightcurves. Lightcurves are FITS files counting the number of photons from a particular source, as a function of time.

The *fv* utility is a software allowing to visualise the content of a FITS file and plot graphs of the data. It is part of the *FTOOLS* suite dedicated to manage FITS files. On the screenshot in illustration 7; we have drawn the count rate of an example file in function of time. This file contains 4 HDUs:

- The Primary HDU is of size zero, so it does not contain any data but is used to store the mandatory keywords in its header
- The RATE extension, containing the (plotted) count rates
- The other two are related to calibration data of the instrument

Also, another useful program of *FTOOL* is *fselect* which allows the creation of a new FITS file from a source file by selecting only rows or columns matching a given condition.

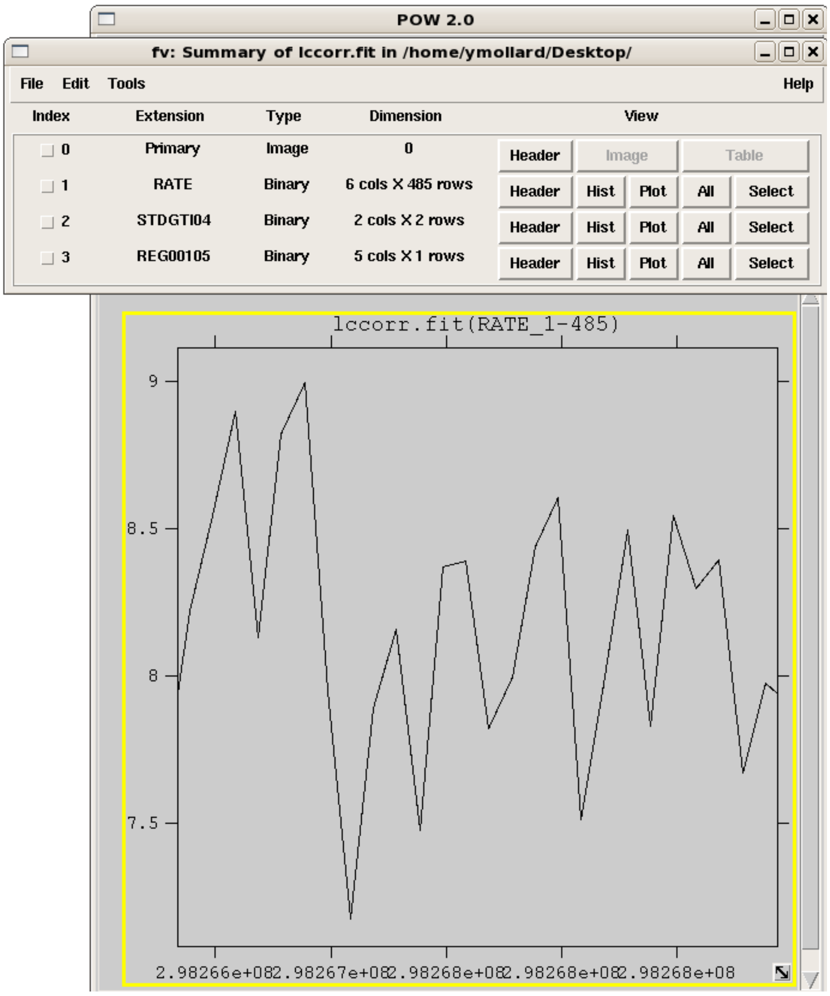


Illustration 7: XMM lightcurve plotted in fv

2.3 XMM-SAS, The XMM-Newton Science Analysis Software

XMM-Newton is an ESA satellite designed to observe X-ray activity in space. It has been launched in 1999. Its name means *X-ray Multi-Mirror* and it has been dedicaced to the scientist Isaac Newton.

To analyze data coming from XMM-Newton, the XMM SOC uses a software suite called the XMM-Newton Science Analysis Software (XMM-SAS or basically SAS). XMM-SAS is a collection of programs, scripts and libraries, specifically designed to reduce and analyse data collected by the XMM-Newton observatory. A program or library within the SAS is called a *task*.

The SAS provides different tools the make data handling and conversion easy. The following tasks were relevant in the context of this internship:

- *STime*: provides time conversion from and to different time representation, Julian date JD, Modified Julian date MJD, Greenwich Meridian Time GMT, Terrestrial time TT, …
- *Barycen*: provides methods to access the JPL ephemerides
- *Parameters*: provides an easy way to check the arguments given to a program, their presence, their definition domain, and to fetch them directly into variables
- *Dal (Data Access Layer):* provides a high-level API to read and write binary files with a common format, including FITS files
- *Celestial*: provides a high-level API to manage matrices, vectors, angles, and convert data in different coordinate systems
- *Errors*: provides a way to log errors uniformly for all tasks in SAS

Of course, these libraries are a tiny part of the abilities of the XMM-Newton Science Analysis Software and their functions could be provided by other external libraries.

2.4 The source data

2.4.1 What it is supposed to contain

The file to decode (named DR005893.F01) was coming from the X-ray spectrometer of the CSM module of Apollo 15. The covered period was during its transearth coast, i.e. from around 4 August to 7 August 1971 [3].

In this file, we were expecting counts of photons from x-ray sources. Data contained in this file should be enough to reproduce the graphics and the conclusions found in all scientific papers [4][1][5].

Particularly, it should be possible to reproduce the graph in illustration 8 from Kuulkers et al. [1], itself taken from Gorenstein et al. [2]. It represents the X-ray activity around the X-ray source Cen-X4 in the Centaurus constellation.

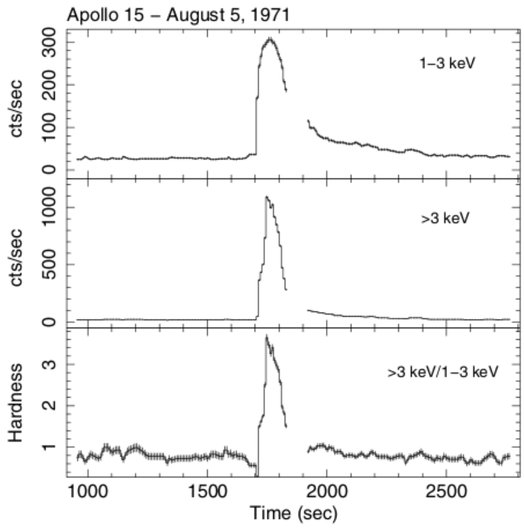


Illustration 8: Light curves of the expected data, taken from [1][2]

2.4.2 Risk of data corruption

The data coming from the spectrometer was initially stored onto a magnetic tape. Previously to the internship, the entire tape had been digitalised into a unique digital binary file, without any other processing or conversion.

The archived tapes are generally stored into underground bunkers. To avoid data loss due to degradation of the magnetic tape itself, they are regularly duplicated onto new tapes or, nowadays, copied on disk. This is the role of NSSDC, to maintain their archives readable and in good state. ESA directly obtained the file from the Internet, without any transfer of tapes or other physical data support. This fact is not insignificant: the original tape is 40 years old and a lot of errors may have been introduced between the original version and the ESA's version. In this case, this could be due to errors introduced while copying or while reading the last version. Moreover, the small size of the file simplifies its transfer by e-mail or usb keys, … and employees could be tempted to send it, forward it, etc... and take the risk to corrupt it. Physicists should remember that an error in the process chain is not impossible and that the original data may have been corrupted.

However, for the internship, we assumed that the ESA's version of the file was intact.

2.4.3 Documentation

Since Apollo 15 is an old mission, and the X-ray fluorescence spectrometer experiment was observed several times during the Apollo program, the amount of documentation about it is considerable and it is not easy to find out the right information scattered in numerous files coming from the NASA's website, its FTP server or from e-mails.

We used mainly the following books, articles or technical documents:

- Transearth Coast X-RAY DataSheet [3]
- Report of the Apollo 15 X-Ray fluorescence experiment [4]
- The Apollo Scientific Experiments Data Handbook [5]
- Preliminary report of the Apollo 15 X-Ray fluorescence experiment [6]
- XMM-Newton SAS documentation [7]
- The Apollo Guidance Computer [8]
- Grumman Apollo News Reference for J missions [9]
- The Apollo 15 and 16 X-ray Fluorescence Experiment [10]
- Apollo 15 Preliminary Science Report [11]

The first step of the internship was to analyse the file, find out the data that it contained, and how it was structured.

3 Deciphering and conversion

3.1 Analysis

The binary file DR005893.F01 was stored on a FTP [12] by NSSDC (National Space Science Data Center). It was very light (around 9MB uncompressed). DR005893 is in fact the name of the **tape**, and it contains the **data** D014016. [3]

Before all, a rapid use of the UNIX tool “strings” showed that the file was really raw and had not got any processing or comments added.

Using a hexadecimal viewer, in a first sight we could see that the data density was not very high and that the file contained numerous NULL values. Like illustrated of figure 9, the following sequence of data seemed to be repeated all along the file:

1) a sequel of ~100 Bytes of non-NULL values, which was supposedly a header
2) a sequel of ~5000 Bytes of sparse data, containing a great number of NULL values and some non-NULL values which did not vary much and were disposed regularly. This was supposedly a table of floats, i.e. the data itself

Illustration 9: General structure

3.1.1 The file format

The first step was to understand how the data was structured inside the file. Two different file formats were provided in the technical documentation [3].

The first format contained a first value NFLAG for each measurement whose value could be:

- NFLAG = 16 when the spectrometer measured data from 1.5keV to 3.0keV
- NFLAG = 96 when the spectrometer was being calibrated, energy range is from 0.75keV to 3.0keV
- NFLAG = 144 when energy range is from 0.75keV to 3.0keV excepted for the first detector from 1.5keV to 6.0keV
- NFLAG = 224 when energy range is from 0.75keV to 3.0keV excepted for the first detector from 1.5keV to 6.0keV, and the spectrometer was being calibrated

On the NSSDC FTP we could indeed find ASCII files starting with such a value (16, 96, 144 and 224). Apparently all of them did not concern the transearth coast but the orbit around the moon.

The second format is represented in illustration 10, it contains records with the following fields:

1) 39 float values from GANDN(1) to GANDN(39) whose four interesting values to help to decipher it were the GMT time and the attitude of the spacecraft (yaw, pitch, roll). An extract is given in appendix 5.2.

2) an integer value NSPECT giving the number of captured spectras
3) a set of NSPECT spectras, i.e. couples (GET, XRAY(220)) where:
    - GET is the ground elapsed time from launch
    - XRAY(220) is a 2x110 table of integers stored by columns

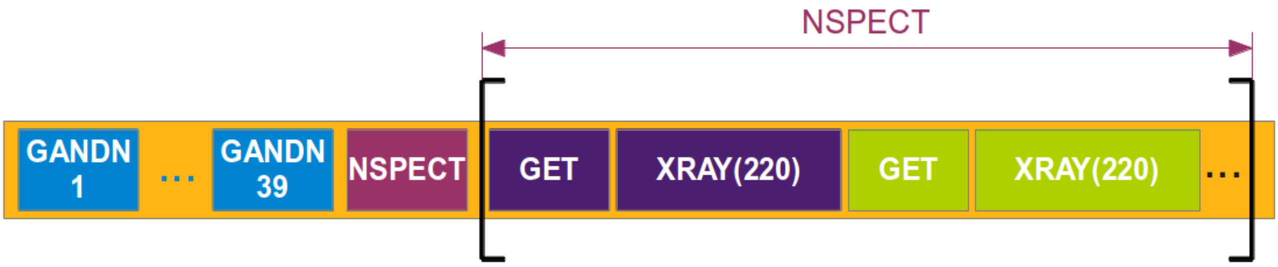


Illustration 10: The second format of a unique record found in the documentation

We first tried to decipher data using both formats and saw if we could find any meaningful value in this context (particularly using times and NFLAG, elapsed time in seconds...). We did not know if the file was recorded in little or big endian and had to try both endianness.

This first try was a failure. In a second attempt we noticed that the regular non-NULL “headers” had a length of 39x4 Bytes. Although we had no information concerning the length of floats, it seemed to be a good key. Assuming this fact, the difference between addresses of two headers divided per 220 gave a length of 4 Bytes for integers in the X-ray table.

Thus, we could infer that the format of the file was indeed the one described in illustration 10. The format description detailed the content of the X-ray table, with indices:

- 1 – 8: The Pulse Shape Modulation PSD and the “total”
- 9 – 12: The Calibration/Attenuate flags (C/A)
- 13 – 38: The X-ray data itself
- 39 – 220: The housekeeping data

This was the only information indicated in the file format. It did not detail the content of the X-ray data, the housekeeping data, what the C/A flags meant, nor what was the total, its precise position in the table, etc.

However, using the length and the binary content of each part, it seemed to be very close to the first format. Particularly, the C/A flags had NFLAG values, and the X-ray data had the same length as the count of Beryllium/Aluminium/Magnesium/Solar Monitor described for the first format.

We concluded that the second format was the raw format of the tape and the first was the ASCII format of the data processed by NASA, but that both formats were made to describe the same data, in a different way.

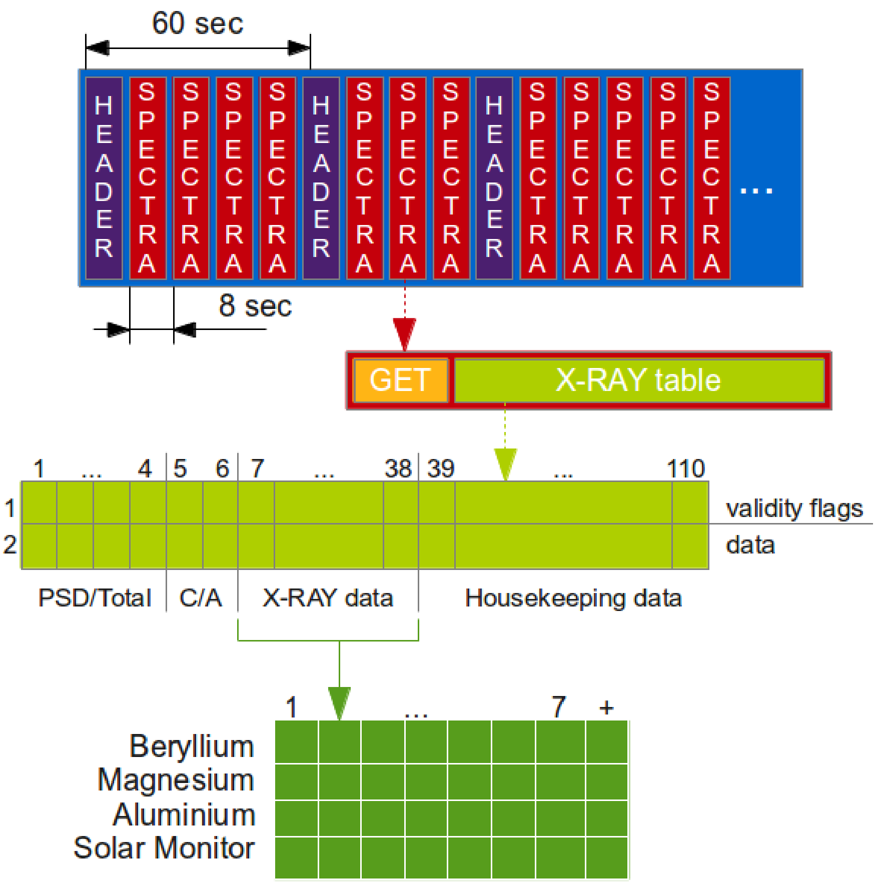


Illustration 11: Logical content of the file

While illustration 10 shows the low-level data (floats and integers) contained in the file as described in the documentation, the deduced global logical content of the file is shown in illustration 11:

The header contains the GANDN values and describes the physical state of the spacecraft as well as general information (time, distances, attitude...). Although it varies, the general time during two headers is 60 sec.

- Each header is followed by zero or n spectras (often 7/8 spectras, but from zero to 64)
- Each spectra contains the Ground Elapsed Time GET in seconds and then the X-RAY table
- The housekeeping data are electronic-level informations about the instrument (voltages, temperatures, …) and are not interesting for our usage at the moment
- The X-RAY table contains two rows. Each element of the first row is a validity flag for the information at the same position in the second row. It contains:
    1) The Pulse Shape Modulation PSD and the total counts of photons, divided per 16 and rounded to the upper value [4][10]
    2) The Calibration/Attenuate flags with which we can deduce the energy range for each detector and whether it is in calibration mode
    3) The X-ray data itself, i.e. the count of each photon received for Beryllium, Magnesium, Aluminium and from the Solar Monitor.

However, two problems remained: interpreted as standard integers or IEEE-754 floats values, the 39 values did not make any sense. The second problem was that the total length of a single measurement in the file did not correspond perfectly to the theoretic length of one measurement in the format. Some Bytes had been added which were not described in the format, probably due to the machine that produced the tape, an IBM 360.

3.1.2 IBM 360/370 data representation

The technical documentation [3][13] indicates some information about how the data are encoded, particularly:

- The tape was generated for IBM 360/370 machines [3][13]
- The block size is variable and does not have a fixed length [3]

  On IBM computers this is called RECFM (RECord ForMat) = VBS (Variable Block Size)
- The dump file contains a 2-Byte header for each block corresponding to its size [13]

Indeed, on IBM 360, data files on tapes were organised into blocks and records, as illustrated on figure 12:

- **Blocks**: Blocks are physical units of data on a tape. Blocks can include a record, part of a record, or multiple records.
- **Records**: Records are logical mappings of the data on a tape. It typically maps directly to the records in a database file.

Illustration 12: Data structure on IBM 360/370

In this example we can see the first two blocks and five records of a file. The given sizes (blocks and records) correspond to those of DR005893.F01. As blocks and records do not make sense for a modern computer, it was necessary to remove it. Thus, the first pass of the program had to read a 2-Byte block header, remove it, jump to the next block thanks to the read offset... and clean the entire file in this way.

Unfortunately it was insufficient. Although IBM documentation specifies that no other header or footer should be added to each block, there were some extra null or non-null Bytes for each block. And the number of the additional Bytes depended on the block size. It could be that they were checksums for error detection, although we did not find any information about it.

Thus, we wrote a first short program to:

- remove block sizes, and any additional termination-Bytes
- trim the file so that it begins with a proper measurement

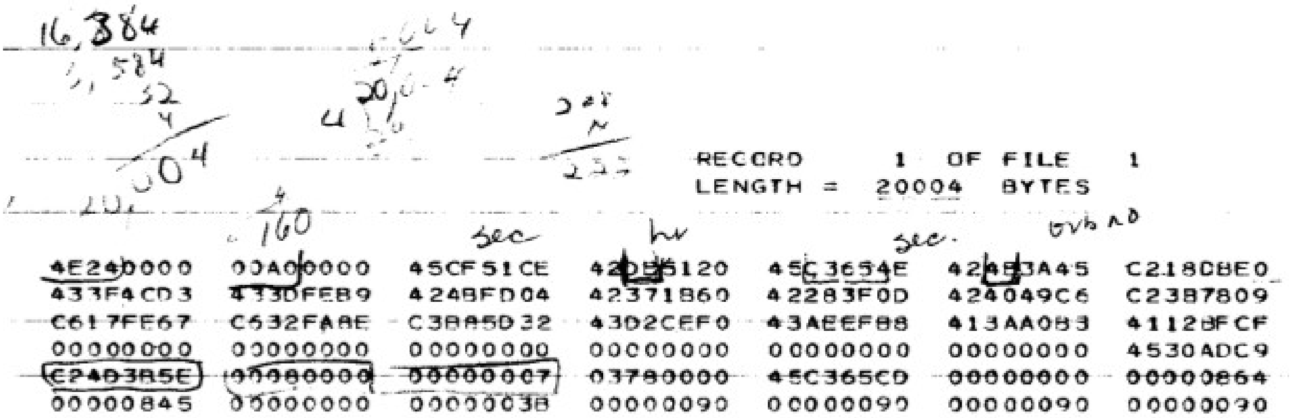
After having created a “cleaned” second file, we could then read the data itself and give a sense to it. The next step was to decode the headers.

3.1.3 Reading the headers

The first mistake was to try to decode the 39 float values of the headers with the standard float representation IEEE-754. Indeed, while this standard was introduced in 1985, our Apollo 15 data is ten years older. According to IBM documentation, the representation of floats on IBM 360 was approximately the same as the actual standard, using powers of sixteen instead of powers of two, except for special values (NaN, infinite, …).

However we could not obtain meaningful data using this representation either. We based our judgement on five fields: the GMT time in seconds, the GET time in hours, the GET time in seconds, and attitude of the spacecraft. The GET time could be any reasonable integer from zero to around 10^5 (even with low values in case it had been reset to zero). The attitude were 3 values yaw, pitch, roll that should be included in -180 and +180° or 0° and 360° or even in radians... And the GMT time in hours could be any possible time from 0 AM to 24 PM.

We found the key while rereading the associate documentation: at the end of the datasheet [3] an extract of the binary file had been printed out in hexadecimal. Someone (probably a NASA engineer) had the brilliant idea to use the datasheet as a draft, circling some values and making some calculations on it, like showed on image 13. This was really helpful to know that we were decoding the file using the right format and to understand how the values had been represented.


RECORD 1 OF FILE 1
LENGTH = 20004 BYTES

4E240000	00A00000	45CF51CE	42D55120	45C3654E	424B3A45	C218DBE0
433F4CD3	433DFEB9	424BFD04	42371B60	42283F0D	424049C6	C23B7809
C617FE67	C632FA8E	C3BA5D32	4302CEF0	43AEEF88	413AA0B3	4112BFCF
00000000	00000000	00000000	00000000	00000000	00000000	4530ADC9
C24D3A5E	00080000	00000007	03780000	45C365CD	00000000	00000864
00000845	00000000	0000003B	00000090	00000090	00000090	00000090

Illustration 13: Notes on the extract of the file

Four pages full of hexadecimal values later, the datasheet included an extract of the ephemeris of Apollo 15. The – human readable – ephemeris included some basic information regarding the state of the spacecraft (time, attitude, altitude, and number of spectras). This extract contained in part the data that we were supposed to found in the GANDN(39) header of each measurement.

Thanks to this key and this ephemeris we could infer the following representation:

A float is represented on 4 Bytes, for instance **`0x 45 CF 51 CE`**.

- The most significant half-Byte indicates the **sign**, 4 for positive, C for negative
- The next half-Byte indicates the **number of hexadecimal characters** necessary to represent the integer part (let's call it **n**, with **n** from **0** to **6**)
- The next **n** characters are the integer part, in powers of two
- Until the end of the 4 Bytes float, this is the fractional part, in negative powers of two

Thus, `0x 45 CF 51 CE` is:

- a positive number
- its integer part, coded on 5 hexadecimal characters is $CF51C_{16} = 849\ 180_{10}$
- its fractional part is given by $E_{16} = 1110_2 = 1x2^{-1} + 1x2^{-2} + 1x2^{-3} + 0x2^{-4}$.

The corresponding float value is +849,180.875. According to the ephemeris extract, this is a correct value for the GET time of Apollo 15 during the transearth coast. This encoding was used for all the 39 floats of GANDN and for the GET times preceding each spectra.

It is important to notice that, as some other information about this file, this encoding was not explained in any datasheet or documentation, it was only an interpretation given after an analysis of the file. Although this encoding gave meaningful results, we cannot guarantee its correctness.

This allowed to produce a CSV file with the 39 values of the 1224 headers, and to show them to the astrophysicists in order to validate whether the read values were meaningful or still incorrect. An extract is given in appendix 5.4. The conclusion was that the found values were perfectly coherent in this context.

3.1.4 Reading the X-RAY table

Recall that each measurement had a header giving some general information (attitude, distances, time...) and contained *zero* or *n* spectras containing themselves a GET time and a X-ray table of 220 integers (see illustration 11).

The number of spectras NSPECT, about it, was a 2-Byte short integer. All integers were encoded in standard powers of two, contrary to floats that used a particular representation. However since modern computers are generally little-endian and the file was big-endian, a call to `ntohl()` was necessary to read correct values.

In this way, the “X-ray” part of the X-ray table could be decoded properly. The counts were small values (generally smaller than 100), which was completely meaningful.

Recall that other parts of the X-ray table were:

- Pulse Shape Discriminator/Total (4 values): The total of counts in the X-ray table were summed, divided per sixteen, rounded to the upper value and stored in the last element of the PSD/Total part. The other 3 fields were Pulse Shape Discriminators for each detector, a value given to help to eliminate non-X-ray events.
- Calibration/Attenuate: These four values seemed to correspond to the NFLAG given in the first format. At least, the values seemed to be the same in most of cases. However we could not figure out why the same flag had been repeated four times and was sometimes set to different values than those given in the documentation.

3.2 Conversion in FITS

After having understood what is contained in this file, the next step was to convert it into a more readable and more modern format, in other words, in one or several FITS file(s). The aim of the conversion was to forget the original binary file and rely on the new one(s), so any single data in the original files had to be present in the output, even if it was wrong or not directly used by scientists.

From a global point of view, the data could be represented as a single plot (in a FITS table) with the GET time in abscissas and count rates of photons in ordinates, as shown in the example of XMM-Newton lightcurve in illustration 7. However to make the data easily readable for scientists, it was necessary to structure the data properly and eventually add some processings.

3.2.1 How to structure the data in FITS

On the X-axis

The total length of the transearth coast of Apollo 15 was 66 hours long. During the coast it has been stabilized seven times to point at seven particular X-ray regions [4], the schedule is shown in table 1. These are the data in what ESAC astrophysicists were most interested and had to access. To provide an easy way for scientists to find out the information they are looking for, it seemed a good idea to create one FITS file per observed source.

However, the observed sources represent only 6 hours on a total of 66 hours. The rest of the information (60 hours of recording) should be stored in (an)other file(s). To simplify the work and understand what they did during the remainder of the time, we have plot the roll, pitch, and yaw of the spacecraft, thanks to the headers, in illustration 14. We can easily recognize the seven observations when the spacecraft stayed steady, which is when the 3 plots stay flat.

Source	Start GET hr:min	Duration hr:min	Date	Start GMT hr:min
Centaurus	226:28	1:05	5 August	00:02
Midgalatic latitude	237:15	0:50	5 August	10:49
Scorpius	245:45	0:35	5 August	19:19
Cygnus	246:35	0:55	5 August	20:09
South galactic pole	261:50	0:55	6 August	11:24
North galactic pole	274:15	0:30	6 August	23:49
Galactic plane anticenter	275:00	1:00	7 August	00:34

Table 1: Astronomical X-Ray Schedule

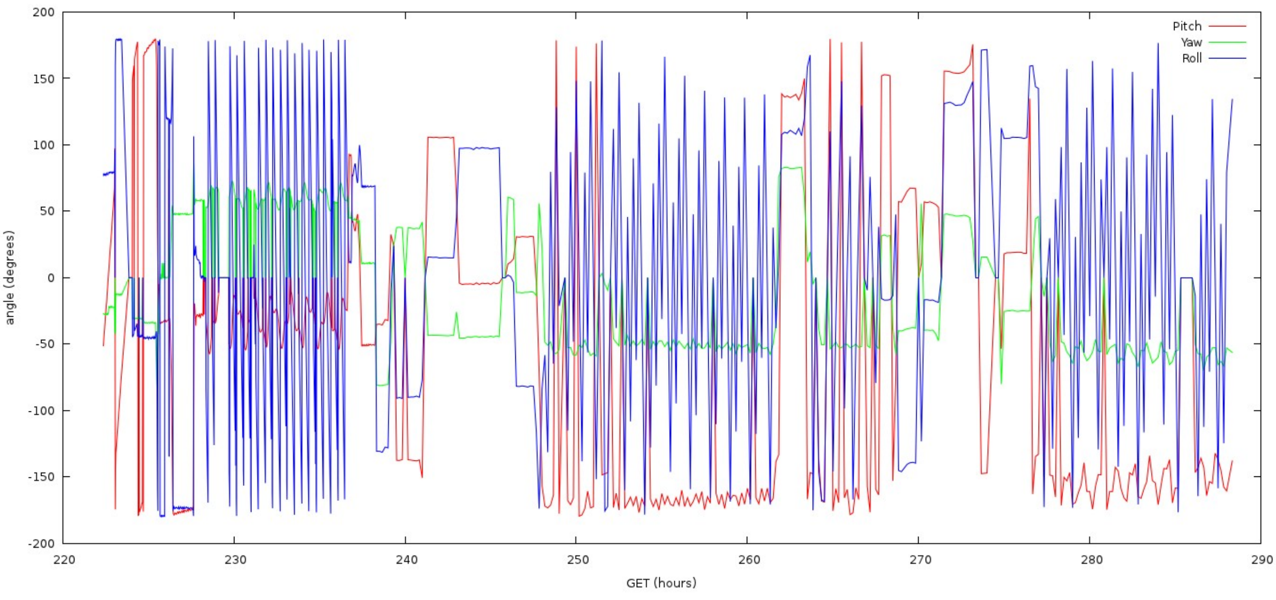


Illustration 14: Yaw, pitch, and roll of the spacecraft during the transearth coast

We observe that the spacecraft's roll is varying continuity and progressively from -180° to +180°, that means that the spacecraft was rolling on itself. This is called the PTC mode (Passive Thermal Control) and ensures that the temperature stayed uniform on the CSM [14].

We have also plotted the last channel (i.e. whose energy >3keV) of the Beryllium filtered counter in illustration 15. We also distinguish in this plot the times when the spectrometer was off (counts = 0) corresponding to the attitude stabilisations of the illustration 14.

The Apollo 15 Mission Report [15] also details the flight plans and particularly when the crew turned on and turned off the experiments conducted in the SIM bay. The plan indicates that the X-ray spectrometer was on during the following times (GET in hr:min):

- 226:25 to 227:40 – CSM was stabilised
- 237:30 to 238:30 – CSM was stabilised
- 245:42 to 249:40 – CSM was stabilised
- 250:50 to 252:00 – CSM was stabilised
- 262:43 to 264:00 – CSM was stabilised
- 267:30 to 271:30 – CSM was stabilised
- 273:00 to 288:40 – CSM was in PTC

Except the last one, all ignitions corresponded more or less to the observed sources planned in table 1. During the last period of the trip the spectrometer was turned on continuously in order to discover new X-ray sources. Thus, during all other periods it is useless to recover the data since the spectrometer was off and the corresponding counts filled with zeros. However, during these periods, if the X-ray tables are full of zeros, the headers are still filled with correct values. This is probably due to the fact that the tape resulting from the X-ray spectrometer is a merge between several tapes coming from different instruments (time measuring, attitude measuring, … and the X-ray spectrometer itself of course).

As scientists are often interested in finding information about a particular source, we only split the timeline in 8 different files: one file per observed source and the last one for the end-of-journey scan where new X-ray sources were discovered.

On the Y-axis

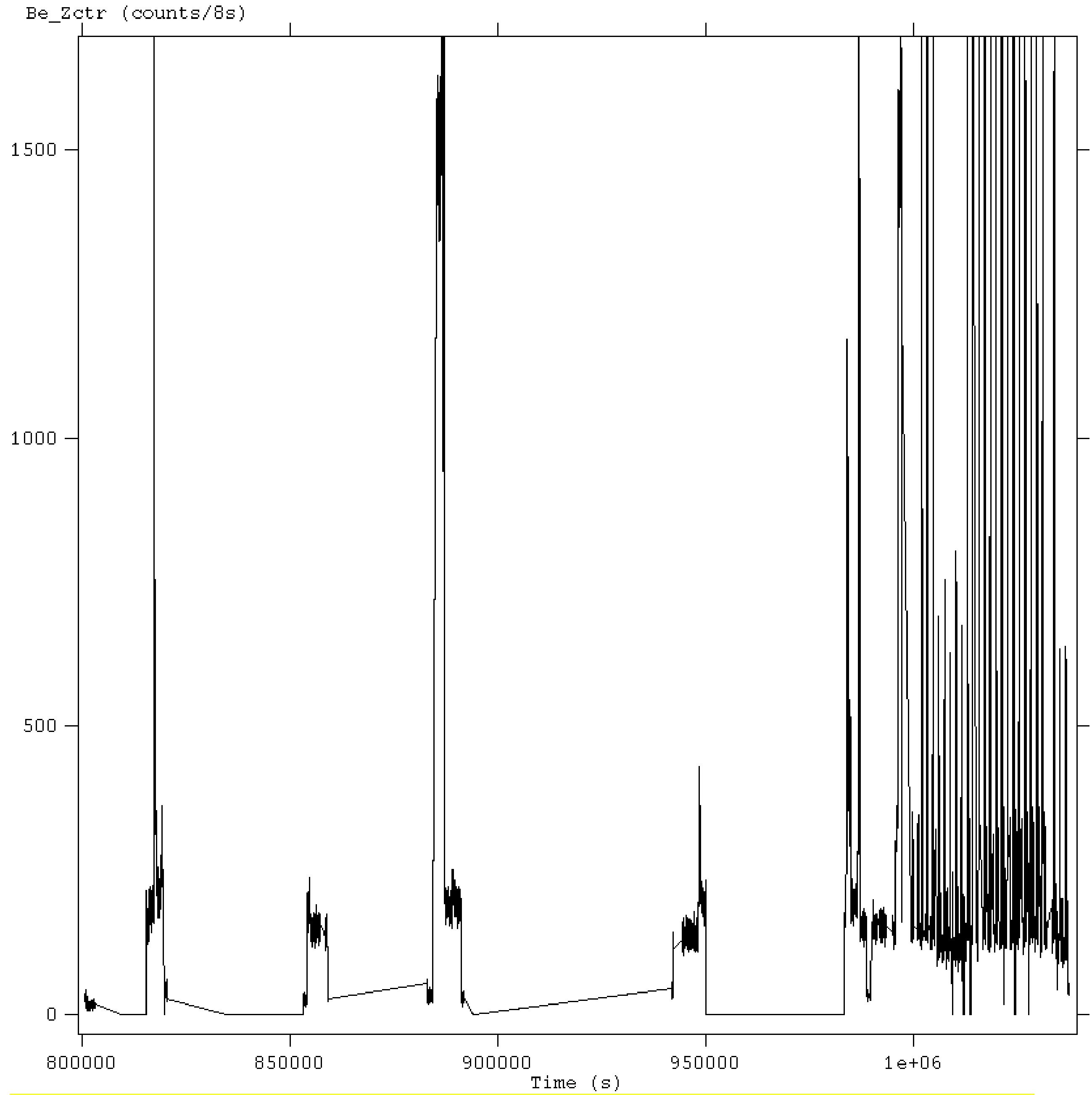


Illustration 15: Last channel (>3keV) of the Beryllium detector during transearth coast

The Y-axis is the count rate of X-ray photons. Count rates were stored using the following way: the scale from ***a*** keV to ***b*** keV is split into 7 continuous energy channels that we called A, B, C, D, E, F, G. For each photon received, the spectrometer selected the channel corresponding to the good energy channel for this scale. Each photon with an energy upper than ***b*** keV was counted in a height channel called Z [4].

Two different energy scales were used during the experience, the first one from 0.75 to 3.0 keV (when the spectrometer was in "normal" mode) and the second one, doubled, from 1.5 to 6.0 keV (when the spectrometer was in "attenuate" mode).

For a different scale we should have produced different FITS file, one FITS file per scale. However in practice the attenuate mode was quite sparse and the attenuate FITS file would have contained very little data and would not have been handy to use for scientists. Thus we produced a unique FITS file and added a field “scale” to identify the scale used.

3.2.2 In-flight calibration data

Periodically, when the spectrometer was running, it ran the “calibration” mode. In this mode a rod of radioactive X-ray sources was placed in front of the first three detectors to calibrate them. This data is not generally useful for scientists afterwards except to check if a detector was faulty or if any error occurred. Theoretically calibration occurred every 16 minutes and lasted 64 seconds [10].

Thus, it seemed to be important to separate calibration data from normal data by creating two FITS files, one for calibration data and the other for normal data. As the solar monitor was not calibrated, all the data coming from it (i.e. the fourth counter) had to be stored in the FITS file keeping “normal” data.

Moreover, it appeared that after each calibration processing the next set of “normal” count had an abnormal peak, so we also moved the next measurement following a calibration processing in the calibration file.

3.2.3 Conversion using XMM-SAS

After a first pass on the file to remove record headers, footers and to trim the file properly, parsed the content of the file, the written conversion program stored it in temporary STL lists, and then used the XMM-SAS API to write down the lists in FITS files.

In order to make the output speak for itself, the maximum of information discovered in the documentation had to be included in the output. Table 2 indicates all information found in the documentation and where it has been moved inside the output FITS files.

Note: the table names as abbreviated as HK = Housekeeping data table, X-RAY = Beryllium, Aluminium, Solar Monitor tables, HD = Header/GANDN table, PHDR = Primary header

Information in doc. or file	Destination in the FITS output
Instrument, spacecraft, begin and end dates, description of the data	FITS attributes in PHDR (“TELESCOP”, “INSTRUME”, “DATE-OBS”, and comments)
Descriptions (resp. units) of headers's parameters	Labels (resp. units) of FITS columns
Validity flags	Column “validity” for each data column in X-RAY tables
GET time preceding each set of spectras	Column “GET time” in HK and X-RAY tables
Scale of energy	Integer in a new column “scale” of X-RAY tables. Associated energy ranges and units described in each column's label
Windows and filters placed in front of detectors	Attribute “FILTER” of X-RAY tables
Pulse Shape Discriminator (PSD)	3 columns for the PSD of the 3 detectors in the HK table. Note: as an entry in the HK table was set each second while the PSD were set each 8 seconds, each PSD value has been duplicated 8 times

Table 2: Destination of information from documentation and file into the FITS output

3.2.4 The housekeeping data

The documentation did not give a lot of details about what was contained in the housekeeping data. It said [3][10] that the following housekeeping data was stored and telemetered to the ground:

1) a sum of all low voltage power supply outputs
2) discriminator reference voltage – 12 V
3) + 6.75 V analog power supply monitor
4) + 5.0 V digital power supply monitor
5) X-ray processor assembly temperature monitor
6) detector temperature monitor
7) low voltage power supply temperature monitor
8) lunar X-ray detector temperature monitor
9) solar X-ray detector temperature monitor

Each one of these nine measurements was repeated each second. As X-ray counting was made on a period of eight seconds, each X-ray table contained eight values for each measurement. Also, a validity flag was associated to each value. Finally the entire housekeeping part of the X-ray table contained 2x8x9 = 144 values.

Unfortunately we were unable to interpret the values of the housekeeping data. Although we knew the units of each field (volts DC or degrees Fahrenheit), the recorded values were integers and we could not find the link between the integers and their equivalent in volts or degrees.

Thus we converted it in a new table as is, with a new row at each second while x-ray data was measured each 8 seconds. In order to be able to check the instrument's health at any time, this table with housekeeping data has been put in both calibration and normal files.

The Pulse Shape Discriminator had also to be inserted in this housekeeping table. The file contained three PSD per X-ray table for the Beryllium, Aluminium and Magnesium filtered counters. Thus a tuple of 3 PSD for each 8 seconds. We copied each 3-tuple 8 times so that it could be inserted in the housekeeping data with a new row each second.

3.3 Pointing direction

Scientists wanted to know, for each time, in which the direction the spectrometer was pointing out, in the equatorial coordinate system. Unfortunately this information was not directly present in the binary file and had to be computed.

The only direction information that we had was in headers (appendix 5.4). The main difficulty in this task lied in finding information in the documentation about:

- How local coordinate systems were defined for the CSM
- What was the exact position and orientation of the SIM bay in the CSM module
- What was the exact orientation of the X-ray detectors in the SIM bay

As shown in illustration 16, the observed sources were located at more than several billions of light-years, so we could assume that the maximum ε angle (CSM-Earth) was close to zero, that the spacecraft stayed fixed at the centre of the Earth and pointed sources located at infinity.

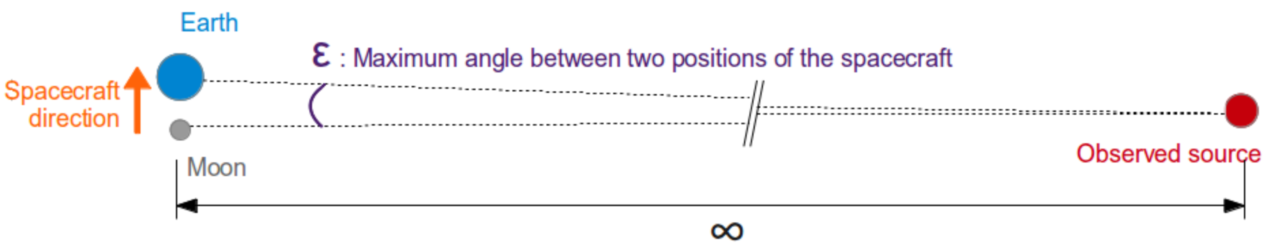


Illustration 16: Observed source at infinity

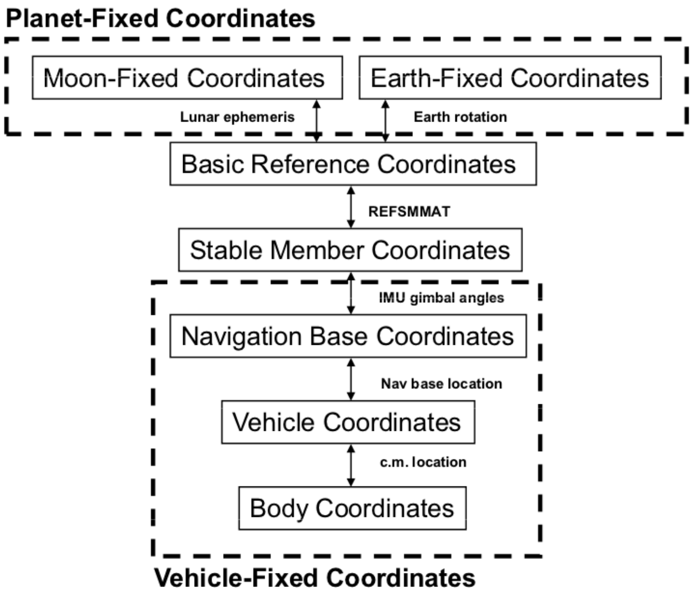


Illustration 17: Coordinate systems used by the CM

3.3.1 A first approach using the REFSMMAT

The Delco Electronics documentation [16], the Apollo News Reference [9] coming from the Apollo spacecraft manufacturer Grumman, and the online Apollo Flight Journal [14] allowed us to understand the several coordinate systems used by the Command Module (illustration 17).

The first coordinate system is the Basic Coordinate System (BCS), whose origin is either the Earth, or the Moon, depending of the strongest gravitational influence. One change of BCS is present in the file at GET 238.25hr when the CSM then feels the gravity of Earth as the stronger force. At this time the BCS is changed to be Earth-centric (while it was a Moon-centric BCS before GET 238.25hr). In term of values in the file this change of BCS produced a jump in attitude values.

In this BCS is defined a REFSMMAT (Reference for a Stable Member Matrix), giving a Stable Member Coordinate System meaningful for each period of the mission (launch, TLI, TEC, and so on). In this SMCS is defined the spacecraft's attitude (roll, pitch, yaw), with the origin at the center of the Inertial Measurement Unit (IMU). The two next coordinate systems bring the triad respectively to a point independent of the mass of the CSM (Located 25.6m under the heat shield) and to the vehicle center of mass. These last two transformations are just translations and irrelevant for us as we are interested only in directions.

During the period covered by the file (from GET 222hr), several REFSMMAT were used: Lift Off on GET 217:50, as well as 221:42. Then aligned to TEI on 221:48 and 226:0. Then to a mode called PTC on 226:08, 237:14, and 250:45. PTC (Passive Thermal Control) is a mode used during both translunar and transearth coasts while the spacecraft was rolling to ensure the best heat distribution. It owned its own REFSMMAT. As all observations were made respectively to the PTC REFSMMAT we ignored the other REFSMMATs even if the file covered a time period using more than one REFSMMAT.

The REFSMMAT during PTC is represented in illustration 18: According to [8][14] the Y axis (pitch) was defined as parallel to the virtual line between the Earth and the Moon at the time of the Trans Lunar Injection (in orange in illustration 2). The TLI took place at GMT July, 26 16:30:03. However the same Y axis is defined by the Delco technical documentation [16] as parallel to the Earth-Moon line at the time of the Trans Earth Injection (start of the green path in illustration 2). Delco was the only document we found giving the numerical values of the REFSMMAT, and the given matrix matched indeed the TEI. Contacted by Erik Kuulkers, David Woods, one of the authors of the AFJ [14] answered that a mistake crept into the AFJ and that the REFSMMAT was indeed defined during the TEI.

The *Studies in Support of the Analysis of Astronomical Data from Apollo 16* paper [17] gave the position of the center line of the SIM bay (containing the X-ray spectrometer) at -37.75° on the roll axis as shown of illustration 5. This was confirmed by a note in the technical datasheet [3].

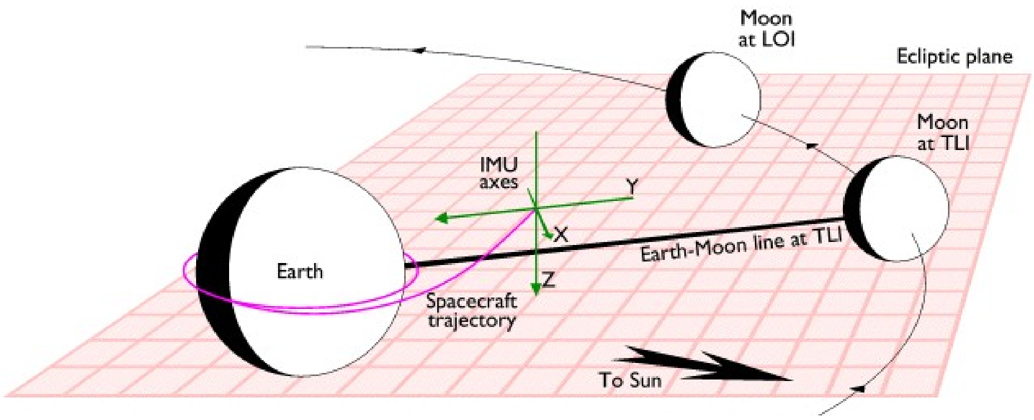


Illustration 18: Apollo's Stable Member Coordinate System during PTC [14]

In the *Studies in support of the analysis of astronomical data from Apollo 16* report [17], the author provides the matrices to use in order to obtain the spectrometer pointing direction from the attitude of the Apollo 16 spacecraft. In a similar way to what he did in his paper, we first tried to compute the instrument direction of Apollo 15 in this way:

1. Rotate the ICRS triad into the REFSMMAT system (using the Moon+Earth ephemeris at the time of T.L.I. computed by the SAS)
2. Rotate the triad resulting from 1. by the roll/pitch/yaw angles
3. Rotate the resulting triad by the fixed angles that define the X-ray instrument into the Service module (-37.75° roll)
4. Invert the resulting total matrix and multiply by the vector that defines the telescope viewing direction in the X-ray instrument frame (the Z axis).
5. The polar coordinates of this resulting vector are the sought alpha/delta coordinates.

Nevertheless we realised later that the given attitude values in the file were not given with respect to the REFSMMAT as they normally used to be but with respect to another coordinate system called Local vertical/Local horizontal (LVLH).

3.3.2 The LVLH coordinate system

LVLH (illustration 19) is a frame of reference that is relative to a line drawn from the spacecraft to the centre of the body it is orbiting, or whose sphere of influence it is in. In this arrangement, the plus-Z axis is along the vertical line towards the planetary centre, the plus-X axis is in the direction of orbital motion parallel to the local horizontal and the plus-Y axis is perpendicular to the orbital plane [14].

Whereas commonly attitude is given with respect to the platform coordinate system (REFSMMAT), the attitude present in the file was given in the LVLH coordinate system, commonly used to define velocity.

To define the X-axis of a LVLH (perpendicular to the motion that we know in GANDN 32, 33 and 34, see appendix 5.4) we would have needed the position of the spacecraft, information that we do not have readily available.

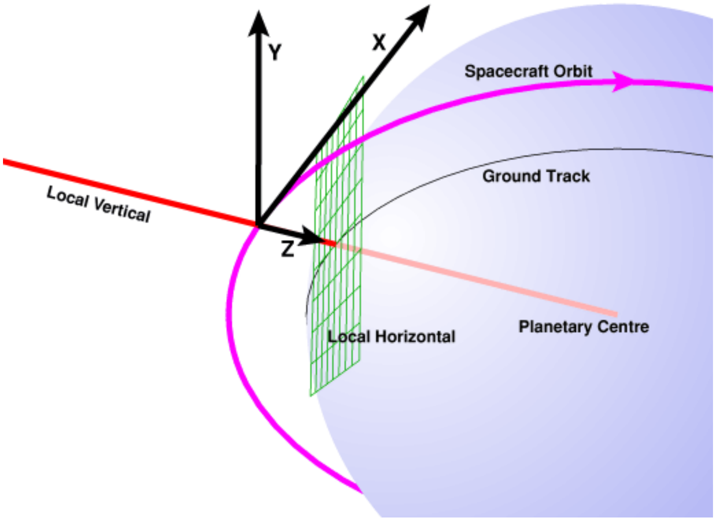


Illustration 19: The local horizontal/local vertical coordinate system [14]

As it appeared to be circuitous we finally gave up the roll, pitch and yaw values to instead use the four look angles available in the file. But we tried different implementations before figuring out that the coordinate systems did not match. To measure how far we were from the right coordinates we compared the computed equatorial coordinated to these of the observed X-ray sources. For instance, at GET = 275.50hr we should obtain the equatorial coordinates of the galactic plane anticenter whose coordinates are well known (R.A. $5^{hr}46'$, Dec. +28° 56').

3.3.3 Look angles to sun/moon and position of the spacecraft

From the CSM point of view, objects were located in space thanks to look angles (latitude and longitude called α and β, see illustration 5). As GANDN headers contained the look angle to sun and the look angle to moon, it was possible to compute the pointing direction using them and the position of moon and sun.

As we had only two look angles and would need three to fix the spacecraft in space, one degree of freedom remained as shown in illustration 20. In this case, knowing the position of the spacecraft would also have fixed the problem.

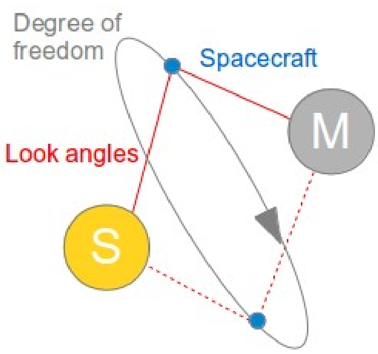


Illustration 20: Degree of freedom with two look angles

While the NASA Apollo Trajectory file (NAT) should be available at NSSDC, obtaining this file would have been more complicated than computing it. In his website Braeunig [18] explained how he computed the trajectory of Apollo 11 using orbital parameters in input (altitude from Earth, velocity, inclination, eccentricity...). Whereas it would be less close from the reality than the actual recorded trajectory, it seemed to be the easier solution.

As the internship came to an end, we did not have enough time to exploit this clue. It would have been necessary to find the correct orbital parameters to use in the documentation and finally compute the pointing direction with the two look angles and the spacecraft's position.

3.4 Tests and error detection

3.4.1 Sanity checks

To make sure that read values were not absurd, it was necessary to verify some sanity checks, i.e. quick checks than cannot guarantee that the read value is correct but that can assert if it is impossible or meaningless. Actually, we had used sanity tests since the first program reading the binary file. At the beginning, when we did not know neither the file format nor the extra-Bytes due to the representation of data on IBM 360/370 tapes, it allowed to exit immediately the reading of a file if a meaningless value was encountered. For instance if we read a GET time of 16.0E-17 seconds that probably meant that we was not actually reading a GET time but we had been posted out by some extra-Bytes compared to the beginning of the next record.

In this context, the following sanity tests were done thanks to calls to `assert()`:

- NSPECT < 1000 – number of spectras, generally from zero to 64 with peaks up to ~200
- 800 000 < GET and GMT in seconds < 1 200 000 (seconds) – corresponds approximately to the period from 3rd to 8th August
- - 180 < any angle < + 180 (degrees) [any angle including attitude, latitude and longitude, except for look angles shifted by 90°]
- 0 < orbit number < 80 – the last valid orbit should be the 74th

The extreme values were determined empirically, and by checking manually if the value seemed to be correct after a sanity check failure.

Thanks to these checks we realised that three times in the whole file we were posted out from four Bytes without any explainable reason. For instance while we were expecting to read a GMT value in seconds (several hundreds of thousands) we got a GET value in hours (several hundreds). In meant than instead of reading GANDN(1) we were reading the next four Bytes GANDN(2). It also meant that the previous X-ray table had its last count set to... a GMT value!

When an assert failed the chosen solution consisted of rewinding four Bytes and continue to read pretending like nothing had happened. Such a rewind printed a warning in the standard output.

Finally all tests were passed successfully with the extreme values above and the rewinding trick.

3.4.2 Validity flags

The binary file already contained validity flags: for each measurement of X-ray detectors, or in the housekeeping data and the headers, an integer flag was associated with it in order to state whether the measurement was ok. This is shown in illustration 11.

Unfortunately the meaning of the flags was not explicitly indicated in the documentation, we had to guess it using the content of the file. As most of the validity flags were set to zero, we assumed that a zero flag was associated to a “right” value and a non-zero positive flag to an incorrect one.

We also observed that a non-zero flag generally implied a singular measurement creating a huge discontinuity when plotting, which consolidated our hypothesis. Non-zero flags were either 1 or 2, but we could not find the exact meaning.

We could remove all data associated to a non-zero flag, however scientists preferred to reprocess the FITS file with usual tools (like *fselect*) to remove the wrong values themselves instead of losing data. The aim of the conversion was to forget the original binary file and rely on the new ones, so any data in the original files had to be present in the output.

3.4.3 Sum check

The counts in the X-ray table were summed up, the total was divided by sixteen, rounded to the upper value and stored in the last element of the PSD/Total part in the X-ray table, according to the documentation and our own data observation.

Although the sum check could be checked later because the both the sum and the counts were present in the FITS file, in order to provide a rapid way to eliminate possibly wrong values we decided to change the validity flag if the provided sum did not match to the computed sum.

As only positive validity flags were used in the original file, we used the negatives values to indicate that sum check failed. The new flag was set to `– abs(expected sum – read sum)`.

As only one sum was provided for each X-ray table, an incorrect sum invalidated the entire table, i.e. the 8 energy channels of the 4 detectors (Beryllium, Aluminium, Magnesium, Solar Monitor).

The computation was undertaken while filling the lists, so that it was easy to iterate on the doubly-linked list to update the validity flag.

3.4.4 Reproducing plots of scientific papers

As a certain number of (more or less old) scientific papers already analysed some part of the data coming from Apollo 15, we had to be able to reproduce it to make sure that we obtained the same data. Scientific papers generally presented the data directly on plots with GET time in abscissas and counts per 8 seconds in ordinates. Below are two examples of plot reproducing.

The first one in illustration 21 is taken from Gorenstein P. & Bjorkholm P. 1972, in Apollo 15: Preliminary Science Report [11]. It shows count rates per 8 seconds on two curves: the first one is the sum of the first seven channels i.e. 1<E<3keV, and the second one is the last channel i.e. E>3keV. Below is the reproduced data plotted in fv, with the same energy range. The holes are due to the removed calibrating data.

The second one in illustration 22 is from Kuulkers et al. [1], again with two plots, 1<E<3keV and E>3keV. Please note that the original plot use a different scale (counts/sec) than the reproduced plot coming from the raw data (counts/8sec), that is why count rates are 8 times lower than the original.

Both plots confirmed a successful interpretation and conversion of data.

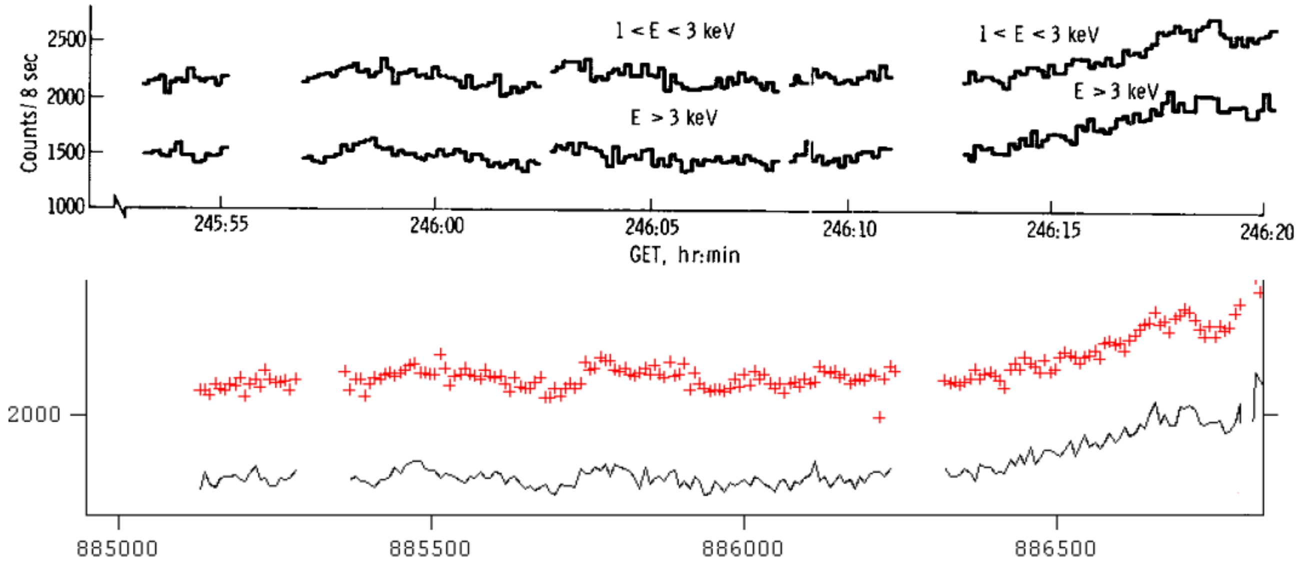


Illustration 21: Plot from the Preliminary Science Report (top) and reproduced plot (bottom)

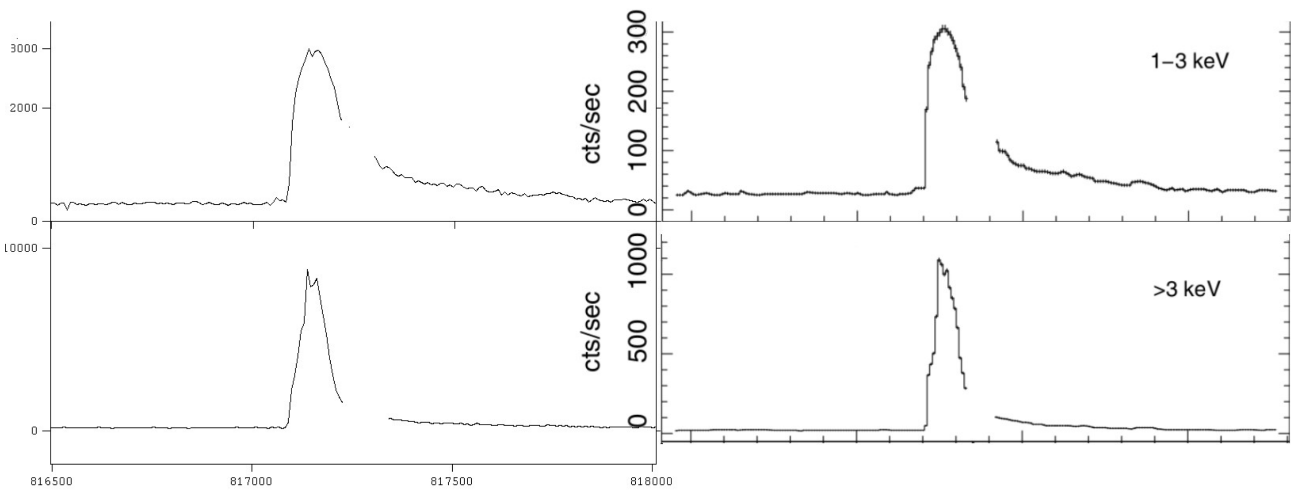


Illustration 22: Plot from Kuulkers et al. (right) and reproduced plot (left)

4 Conclusion

To conclude on this 3-month internship, the main goals of the project were reached, that is to say analyse the file, determine its format and encoding and then convert it into FITS files. Recall that the original file has been transmitted by NASA with some elements of description but with no precise documentation describing the content. Before writing any program to convert a file within an unknown format into FITS files that we could not even imagine their structure because we did not know the input's content, we needed to document a bit.

The first challenge was to interconnect all informations we had from descriptions and technical reports about Apollo 15, Apollo 16 and the experiments of the SIM bay. This helped to understand how the X-ray fluorescence spectrometer experience was conducted and what was the content of its output file. Thus, apart from being a programming project it was also a work of information retrieval in the Apollo program documentation that must represent, in total, more than several hundreds of Megabytes of digitalized old technical reports and scientific papers. If this retrieval work had to be a precondition to begin the deciphering, in practice it has been conducted all along the project, until its last hours, and each document brought an additional information to understand a detail in the experiment, an explanation about the output file, or any help to give a scientific meaning to this 8MB sequence of bits.

Once we understood what the data contained, how it was structured and encoded we could think to how to structure the output file(s) in order to make this data easily accessible for scientists. It had to faithfully represent the original file and at the same time simplify access to the information. We could then begin programming to create a program making the conversion between the *well-defined* input into the *well-defined* output. The program itself was really elementary, it was just a matter of sequentially reading some Bytes, applying some low-level operations like shifts or binary masks and writing the same Bytes in the right place.

In two months the conversion was done and the first FITS files were submitted. As all the data contained in the original file – and even some elements of documentation and description – have been inserted in the output, the old IBM-360-compatible file can now be forgotten and scientists can directly read the data in a format that they are used to manipulating.

Then came the need to know, at each point in time, where the instrument was pointing in ICRF coordinates. It took up the last month and finally it is still not finished. This task required at least the same quantity of information as deciphering the binary file, if not more. This is why we kept looking for reports and any piece of documentation until the last minute. It was a fight between the information that we knew, the information that we did not know, the information that we thought true, and the information which had contradictory sources. In this way, after having understood the sequence of the coordinate system, the change of the BCS at 238hr, the different REFSMMATs..., after having implemented it and seeing that it gave a wrong result with regard to the observations done, we realised that the attitude was not given in the casual coordinate system but in a coordinate system usually used to defined velocity (LVLH). Then we switched to the look angles that were not enough to compute the pointing direction. And then the internship came to an end without letting us enough time to sort out the problem using the other 34 trajectory fields.

But even if this last goal was not completely achieved we learned a lot about the Apollo missions, and this step was necessary to understand what we did and which data we were manipulating. However thanks to the computed position it should be possible to definitely solve the problem, either using the look angles, which seems the easier way, or by defining the LVLH coordinate system and using the spacecraft's attitude.

This 3-month internship at the European Space Astronomy Center was a unique experience, and rummaging through history to find informations about this 40-years-old mission has been really instructive and fascinating. It also gave me a first approach to the world of space, spacecrafts and astronomy, a domain in which I may orient my professional career.

It is clear that computing science fully plays its role helping man discovery the – fantastically huge – environment surrounding our planet. The most significant example project at ESA is probably GAIA, this satellite expected to be launched in 2013, which will sweep the sky with 106 CCD, each one with a resolution of 4500×1966 pixels. GAIA will determine the positions and motions of more than 1 billion stars with an accuracy of 20 μas generating about 60 TB of compressed data. The enormous computation power to fulfil this challenge is evaluated to 6000 GFlops/sec. This power should be achieved by a cluster of about 150 of multicore processors. In this mission computer scientists astrophysicists of ESAC, Cambridge university and the Geneva observatory are joining their competence to allow GAIA to produce its final catalogue of 1 billion objects.

5 Appendixes

5.1 Ephemeris listing of Apollo 15 [3]

EPHEMERIS LISTING OF APOLLO 15

D-14016

HR	MIN	SEC	SEC.	LAT.	LONG.	THETA	PSI	PHI	ALTITUDE	SPECTRA
222	19	1	800340.88	-24.86	98.05	-59.47	-27.61	77.55	138.38	7
222	20	1	800400.88	-24.06	94.92	-57.33	-27.68	77.65	137.88	8
222	21	1	800460.88	-23.20	91.82	-54.32	-27.30	77.11	137.33	7
222	22	1	800520.88	-22.28	88.76	-51.21	-26.95	77.85	136.74	8
222	23	1	800580.88	-21.30	85.74	-48.52	-27.14	77.20	136.11	7
222	24	1	800640.88	-20.27	82.76	-44.87	-27.48	78.06	135.43	8
222	25	1	800700.88	-19.19	79.82	-41.83	-27.61	77.40	134.72	7
222	26	1	800760.88	-18.06	76.91	-39.42	-27.52	77.57	133.97	8
222	27	1	800820.88	-16.89	74.04	-36.61	-27.56	77.88	133.18	7
222	28	1	800880.88	-15.68	71.20	-33.50	-27.80	77.34	132.36	8
222	29	1	800940.88	-14.43	68.40	-30.16	-27.03	77.91	131.52	7
222	30	1	801000.88	-13.15	65.62	-27.27	-27.13	77.80	130.64	8
222	31	1	801060.88	-11.83	62.87	-24.45	-27.20	77.28	129.74	7
222	32	1	801120.88	-10.49	60.15	-21.80	-27.42	77.88	128.81	8
222	33	1	801180.88	-9.13	57.44	-19.26	-27.54	78.44	127.87	7
222	34	1	801240.88	-7.74	54.75	-16.81	-27.71	78.87	126.90	8
222	35	1	801300.88	-6.34	52.08	-12.18	-27.19	78.19	125.92	7
222	36	1	801360.88	-4.92	49.42	-9.93	-27.70	77.55	124.93	8
222	37	1	801420.88	-3.49	46.77	-6.57	-27.18	77.62	123.93	7
222	38	1	801480.88	-2.05	44.12	-3.32	-26.82	77.69	122.92	8
222	39	1	801540.88	-0.60	41.47	-0.25	-27.16	77.78	121.90	7
222	40	1	801600.88	0.85	38.83	2.69	-25.27	78.45	120.88	8
222	41	1	801660.88	2.30	36.17	5.50	-21.72	79.32	119.87	7
222	42	1	801720.88	3.74	33.51	8.36	-21.93	79.36	118.85	8
222	43	1	801780.88	5.18	30.84	11.65	-22.50	78.98	117.85	7
222	44	1	801840.88	6.61	28.16	14.94	-22.70	79.42	116.85	8
222	45	1	801900.88	8.03	25.45	18.05	-22.32	79.60	115.86	7
222	46	1	801960.88	9.43	22.72	21.25	-21.94	79.19	114.89	8
222	47	1	802020.88	10.81	19.97	23.75	-22.17	79.47	113.94	7
222	48	1	802080.88	12.17	17.19	26.45	-22.22	79.58	113.00	8
222	49	1	802140.88	13.50	14.38	29.58	-21.59	79.08	112.09	7
222	50	1	802200.88	14.80	11.54	32.35	-22.36	79.26	111.20	5
222	51	1	802260.88	16.06	8.66	35.35	-22.50	79.23	110.34	7
222	52	1	802320.88	17.29	5.74	38.53	-22.19	78.87	109.51	8
222	53	1	802380.88	18.48	2.77	41.93	-21.75	79.61	108.71	7
222	54	1	802440.88	19.62	-0.23	45.31	-22.03	79.40	107.95	8
222	55	1	802500.88	20.72	-3.28	48.30	-22.33	78.90	107.23	7
222	56	1	802560.88	21.76	-6.37	50.79	-22.40	79.47	106.54	8
222	57	1	802620.88	22.74	-9.51	53.59	-22.40	79.23	105.89	7
222	58	1	802680.88	23.66	-12.70	57.42	-22.57	79.11	105.29	8
222	59	1	802740.88	24.52	-15.93	60.61	-22.41	79.23	104.73	7
223	0	1	802800.88	25.30	-19.20	63.71	-22.09	79.94	104.22	8
223	1	1	802860.88	26.02	-22.52	67.61	-22.07	79.49	103.75	7
223	2	1	802920.88	26.66	-25.88	97.34	-41.49	95.95	103.34	0
223	2	58	802977.88	27.19	-29.11	0.0	0.0	0.0	102.99	0
223	3	58	803037.88	27.67	-32.54	-174.46	-42.53	159.80	102.67	0
223	4	58	803097.88	28.07	-35.99	-143.78	-22.36	176.34	102.41	0
223	5	58	803157.88	28.38	-39.47	-132.18	-12.27	178.98	102.20	0
223	6	58	803217.88	28.60	-42.97	-129.41	-12.55	179.47	102.04	0
223	7	58	803277.88	28.73	-46.47	-126.79	-12.20	179.63	101.94	0

5.2 CSV extract of the headers

header number	GANDN(1) GMT (s)	GANDN(2) GET (hr)	GANDN(3) GET (s)	GANDN(4) orbit number	GANDN(5) latitude (deg)	GANDN(6) longitude (deg)	GANDN(15) pitch (deg)	GANDN(16) yaw (deg)	GANDN(17) roll (deg)
1	849360.875000	222.366913	800520.875000	75.253433	-22.280624	88.761383	-51.208130	-26.952316	77.851364
2	849420.875000	222.383575	800580.875000	75.261826	-21.303192	85.741791	-48.523895	-27.138931	77.201019
3	849480.875000	222.400238	800640.875000	75.270096	-20.272202	82.760971	-44.868713	-27.484451	78.059418
4	849540.875000	222.416901	800700.875000	75.278275	-19.190964	79.818161	-41.825134	-27.606033	77.401276
5	849600.875000	222.433563	800760.875000	75.286346	-18.062805	76.912201	-39.424255	-27.521149	77.572449
6	849660.875000	222.450226	800820.875000	75.294327	-16.891052	74.041565	-36.607574	-27.557007	77.877930
7	849720.875000	222.466888	800880.875000	75.302200	-15.679001	71.204407	-33.497391	-27.796967	77.335602
8	849780.875000	222.483551	800940.875000	75.309998	-14.429934	68.398636	-30.159622	-27.033615	77.911163
9	849840.875000	222.500244	801000.875000	75.317703	-13.147095	65.621933	-27.266953	-27.133560	77.798386
10	849900.875000	222.516907	801060.875000	75.325348	-11.833694	62.871735	-24.454666	-27.200470	77.279770
11	849960.875000	222.533569	801120.875000	75.332916	-10.492905	60.145340	-21.802719	-27.423996	77.879593
12	850020.875000	222.550232	801180.875000	75.340439	-9.127861	57.439880	-19.258209	-27.544952	78.439972
13	850080.875000	222.566895	801240.875000	75.347900	-7.741667	54.752380	-16.814728	-27.708954	78.866867
14	850140.875000	222.583557	801300.875000	75.355331	-6.337402	52.079758	-12.182590	-27.185913	78.187393
15	850200.875000	222.600220	801360.875000	75.362717	-4.918121	49.418823	-9.930460	-27.699921	77.551498
16	850260.875000	222.616913	801420.875000	75.370087	-3.486865	46.766373	-6.570224	-27.179977	77.615723
17	850320.875000	222.633575	801480.875000	75.377441	-2.046670	44.119095	-3.321585	-26.823013	77.687714
18	850380.875000	222.650238	801540.875000	75.384796	-0.600574	41.473648	-0.252942	-27.163940	77.778427
19	850440.875000	222.666901	801600.875000	75.392136	0.848374	38.826691	2.686134	-25.267349	78.448151
20	850500.875000	222.683563	801660.875000	75.399506	2.297103	36.174835	5.496763	-21.724884	79.318726
21	850560.875000	222.700226	801720.875000	75.406891	3.742514	33.514679	8.362383	-21.927277	79.355606
22	850620.875000	222.716888	801780.875000	75.414322	5.181465	30.842865	11.648470	-22.504013	78.983704
23	850680.875000	222.733551	801840.875000	75.421783	6.610770	28.155991	14.942385	-22.704651	79.423386
24	850740.875000	222.750244	801900.875000	75.429291	8.027184	25.450760	18.046982	-22.315063	79.595169
25	850800.875000	222.766907	801960.875000	75.436874	9.427397	22.723862	21.253403	-21.938187	79.194931
26	850860.875000	222.783569	802020.875000	75.444519	10.808029	19.972092	23.748001	-22.168488	79.465500
27	850920.875000	222.800232	802080.875000	75.452240	12.165621	17.192337	26.454773	-22.215271	79.576096

5.3 CSV extract of the X-ray table

spectra	1		2		3		4		5		6		
	valid	counts	valid	counts	valid	counts	valid	counts	valid	counts	valid	counts	
Total PSD	0	2026	0	2107	0	2110	0	2023	0	2010	0	2038	
	0	2082	0	2119	0	2142	0	2141	0	2064	0	2127	
	0	2040	0	2040	0	2080	0	2109	0	2074	0	2022	
	0	55	0	55	0	58	0	60	0	55	0	56	
Calibration Attenuate	144	144	144	144	144	144	144	144	144	144	144	144	
	144	144	144	144	144	144	144	144	144	144	144	144	
X-RAY data	0	19	0	20	0	17	0	18	0	17	0	11	Beryllium 1
	0	7	0	6	0	7	0	6	0	7	0	12	Beryllium 2
	0	7	0	12	0	4	0	8	0	11	0	11	Beryllium 3
	0	6	0	6	0	8	0	7	0	6	0	10	Beryllium 4
	0	8	0	7	0	8	0	11	0	6	0	8	Beryllium 5
	0	10	0	4	0	11	0	5	0	7	0	7	Beryllium 6
	0	4	0	6	0	8	0	9	0	1	0	3	Beryllium 7
	0	29	0	34	0	24	0	29	0	27	0	25	Beryllium +
	0	16	0	14	0	11	0	16	0	17	0	10	Magnesium 1
	0	3	0	3	0	6	0	6	0	6	0	7	Magnesium 2
	0	4	0	2	0	2	0	4	0	4	0	7	Magnesium 3
	0	2	0	0	0	6	0	3	0	4	0	6	Magnesium 4
	0	1	0	3	0	3	0	1	0	7	0	4	Magnesium 5
	0	3	0	6	0	6	0	5	0	2	0	4	Magnesium 6
	0	5	0	2	0	6	0	6	0	3	0	1	Magnesium 7
	0	23	0	14	0	22	0	26	0	30	0	20	Magnesium +
	0	19	0	13	0	19	0	12	0	10	0	16	Aluminium 1
	0	9	0	5	0	5	0	12	0	5	0	4	Aluminium 2
	0	5	0	6	0	5	0	7	0	6	0	3	Aluminium 3
	0	5	0	2	0	5	0	3	0	3	0	7	Aluminium 4
	0	3	0	4	0	7	0	5	0	3	0	4	Aluminium 5
	0	7	0	9	0	9	0	9	0	7	0	7	Aluminium 6
	0	5	0	6	0	5	0	4	0	4	0	4	Aluminium 7
	0	39	0	39	0	42	0	47	0	38	0	29	Aluminium +
	0	69	0	91	0	71	0	87	0	93	0	83	Solar Monitor 1
	0	266	0	250	0	276	0	250	0	217	0	280	Solar Monitor 2
	0	110	0	108	0	119	0	130	0	127	0	116	Solar Monitor 3
	0	17	0	24	0	24	0	23	0	14	0	22	Solar Monitor 4
	0	11	0	7	0	12	0	10	0	2	0	7	Solar Monitor 5
	0	5	0	8	0	8	0	12	0	11	0	8	Solar Monitor 6
	0	7	0	5	0	8	0	9	0	11	0	7	Solar Monitor 7
	0	154	0	163	0	164	0	173	0	170	0	152	Solar Monitor +
Housekeeping Data	0	199	0	199	0	199	0	199	0	199	0	199	
	…	…	…	…	…	…	…	…	…	…	…	…	
	0	199	0	199	0	199	0	199	0	199	0	199	
	0	202	0	202	0	202	0	202	0	202	0	202	
	…	…	…	…	…	…	…	…	…	…	…	…	
	0	202	0	202	0	202	0	202	0	202	0	202	
	0	198	0	198	0	198	0	198	0	198	0	198	
	…	…	…	…	…	…	…	…	…	…	…	…	
	0	198	0	198	0	198	0	198	0	198	0	198	
	12	160	12	160	12	160	12	160	12	160	12	160	
	…	…	…	…	…	…	…	…	…	…	…	…	
	12	160	12	160	12	160	12	160	12	160	12	160	
	12	107	12	107	12	107	12	107	12	107	12	107	
	…	…	…	…	…	…	…	…	…	…	…	…	
	12	107	12	107	12	107	12	107	12	107	12	107	
	0	123	0	123	0	123	0	123	0	123	0	123	
	…	…	…	…	…	…	…	…	…	…	…	…	
	0	123	0	123	0	123	0	123	0	123	0	123	
	0	94	0	94	0	94	0	94	0	94	0	94	
	…	…	…	…	…	…	…	…	…	…	…	…	
	0	94	0	94	0	94	0	94	0	94	0	94	
	0	76	0	76	0	76	0	76	0	76	0	76	
	…	…	…	…	…	…	…	…	…	…	…	…	
	0	76	0	76	0	76	0	76	0	76	0	76	

5.4 GANDN parameters of headers

Description of the 39 GANDN parameters (trajectory information). Those in bold played an important role in deciphering and trying to compute the position direction.

1) Greenwich Mean Time from midnight preceding launch (sec.)
2) **Ground Elapsed Time from launch (hr.)**
3) **Ground Elapsed Time from launch (sec.)**
4) Current incremental revolution (n.d.)
5) Selenographic latitude with 0 deg being the equator of the moon (deg.)
6) Selenographic longitude (deg.)
7) Selenographic radius (ft.)
8) Lunar inertial velocity (fps)
9) Apolune radius (ft.)
10) Perilune radius (ft.)
11) Apolune altitude (n.mi.)
12) Perilune altitude (n.mi.)
13) **Vehicle look angle to moon (deg.)**
14) **Vehicle look angle to moon (deg.)**
15) **Vehicle pitch (deg.)**
16) **Vehicle yaw (deg.)**
17) **Vehicle roll (deg.)**
18) Position x component in lunar orbit moon centered (ft.)
19) Position y component in lunar orbit moon centered (ft.)
20) Position z component in lunar orbit moon centered (ft.)
21) Velocity x component in PACSS lunar orbit moon centered (fps)
22) Velocity y component in PACSS lunar orbit moon centered (fps)
23) Velocity z component in PACSS lunar orbit moon centered (fps)
24) Acceleration x component in lunar orbit moon centered (ft/sec^2)
25) Acceleration y component in lunar orbit moon centered (ft/sec^2)
26) Acceleration z component in lunar orbit moon centered (ft/sec^2)
27) Altitude above the lunar landing site (ft.)
28) Altitude rate in lunar orbit (ft.)
29) Sensed acceleration x component in platform coordinates (ft/sec^2)
30) Sensed acceleration y component in platform coordinates (ft/sec^2)

31) Sensed acceleration z component in platform coordinates (ft/sec²)

32) Sensed velocity x component in platform coordinates (fps)

33) Sensed velocity y component in platform coordinates (fps)

34) Sensed velocity z component in platform coordinates (fps)

35) Geodetic altitude (n.mi.)

36) Sun look α angle in the sun vector system (deg.)

37) Sun look β angle in the sun vector system (deg.)

38) Vehicle α look angle to the sun (deg.)

39) Vehicle β look angle to the sun (deg.)

6 Glossary, index and acronyms

AFJ – Apollo Flight Journal	Apollo Flight Journal [14]
Attitude – Roll, pitch, Yaw	Set of the three angles (roll, pitch, yaw) defining the spacecraft's orientation in space. See 2.1.2 and 3.1.1.
BCS – Basic Coordinate System	Spacecraft's coordinate system, centered in its center of mass. See 2.1.2.
CM – Command module	Cabin housing the crew and equipment needed for re-entry and splashdown.
CSM – Command/Service module	Spacecraft in charge of the transportation of astronauts between Earth and Moon. Until the jettisoning of the Command Module in the ocean, both stay docked together.
CSV – Comma Separated Values	File format for spreadsheets easily generated on the standard output as it uses commas and new-lines to define lines and columns.
Dec – Declination	Second composite of an object's coordinates in space in the Equatorial Coordinate System. See 2.1.1.
Endianness	Ordering of Bytes of a file stored in memory. The little-endian ordering stores a file from the least significant Byte to the most significant Byte.
Ephemeris	Position in the sky of a star, spacecraft or any astronomical object, at given times.
GANDN	39 Ephemeris values in the headers encountered in the binary file. See 3.1.1.
GET – Ground Elapsed Time	Time elapsed since the launch, in seconds or hours. See 2.1.2 and 3.1.1.
GMT – Greenwich Meridian Time	Time elapsed since midnight preceding launch, in seconds. See 2.1.2 and 3.1.1.
HDU – Header Data Unit	Segment of a FITS files (Primary HDU or an extension) See 2.2.
ICRF/ICRS – International Celestial Reference Frame/System	The Earth-centered Cartesian equatorial system having the +z axis pointing along the axis of rotation of the earth and the +x axis pointing in the direction of the vernal equinox. See 2.2.1.
IMU – Inertial Measurement Unit	Device measuring the spacecraft's velocity and attitude
Look angles	Object's coordinates in the BCS. See 2.1.2.
LVLH – Local Horizontal	Coordinate System generally used to define velocity. See 3.3.2.

Local Vertical	
NSSDC – National Space Science Data Center	The NASA's permanent archive for space science mission data.
PSD – Pulse Shape Discriminator	Integer value helping to exclude non X-ray counts. One PSD was recorded for each detector in each header. See 3.1.4.
PTC – Passive Thermal Control	Also called the "barbecue mode", the PTC is the continuous rolling of the spacecraft around itself to ensure an uniform repartition of the sun heat.
RA – Right Ascension	First composite of an object's coordinates in space in the Equatorial Coordinate System. See 2.1.1.
REFSMMAT – REFerence to a Stable Member MATrix	Matrix changing the CSM platform alignment. Eight different REFSMMAT were used in total during the whole mission. These eight changes aimed to ensure that attitude corresponded to meaningful values in the point of view of the crew, depending of the phase of the mission and the orientation of the CSM (launch, insertions, orbits, coasts...). See 3.3.1.
SIM bay – Scientific Instrument Module	Part of the CM used to contain all the scientific experiments. See illustration 5.
SIM bay – Scientific Instrument Module	Part of the Service module hosting Scientific Experiments, including the X-ray fluorescence spectrometer.
SM – Service module	Module providing propulsion, electrical power and storage, and hosting the scientific equipment in the SIM bay.
SMCS – Stable Member Coordinate System	Coordinate system where the attitude is defined in. See 3.3.1.
Spectra	Designs the couple GET value + X-ray table. See 3.1.1.
SPS engine	Service Propulsion System: engine ensuring propulsion to the CSM. Its nozzle exceeds at the bottom of the CSM.
STL – Standard Template Library	The C++ Standard Template Library, providing an implementation of containers like lists, vectors, maps...
TEC – Transearth coast	Journey from the Moon to the Earth. See 1.2.1.
TLI – Translunar Injection	Designs the moment where engines are ignited to put the spacecraft in direction of the Moon. See 1.2.1.
X-ray table	2x110 elements matrix whose first line is the photon counts for the eight channels of each of the four detectors, and whose second line is validity flags. See 3.1.1.

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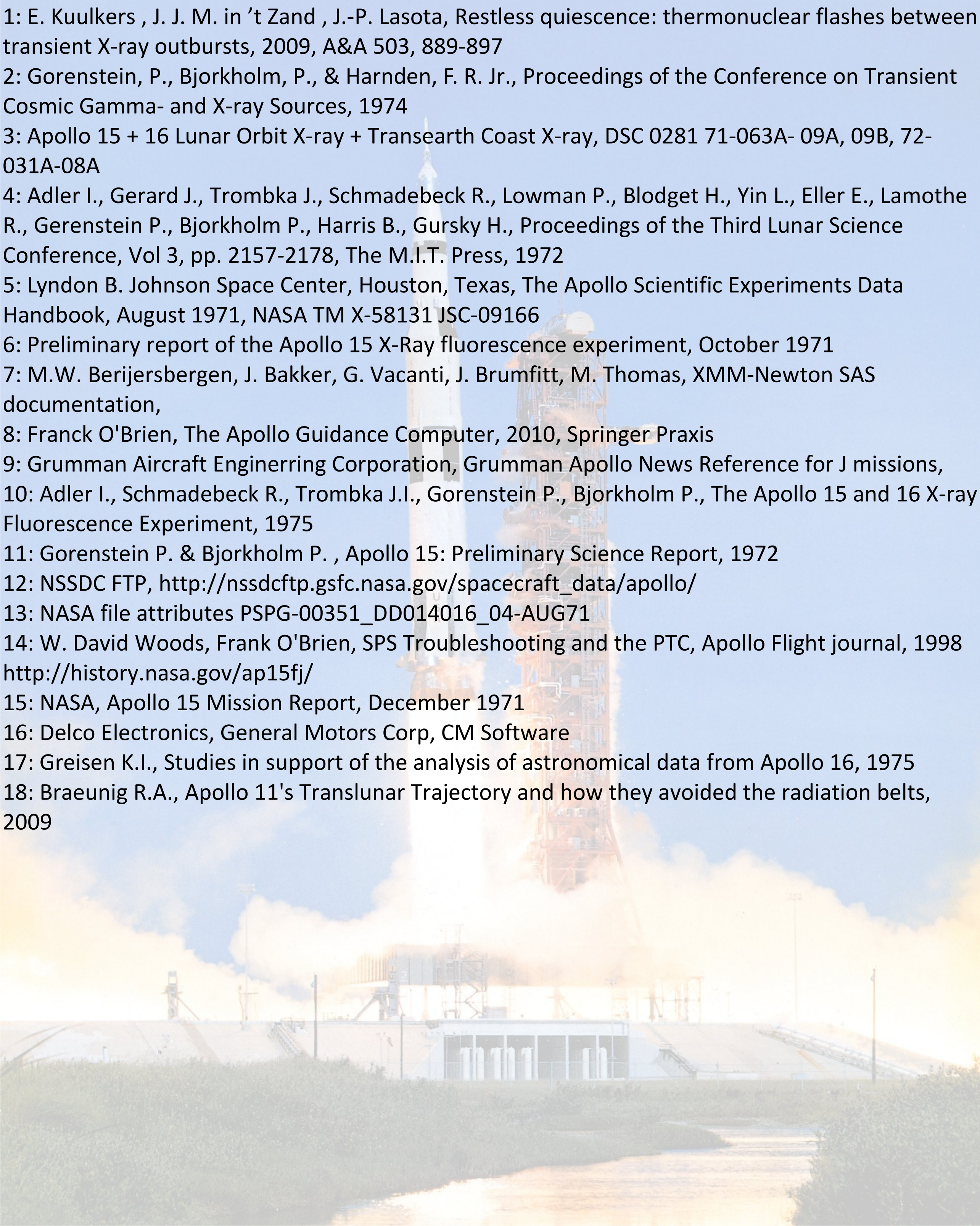
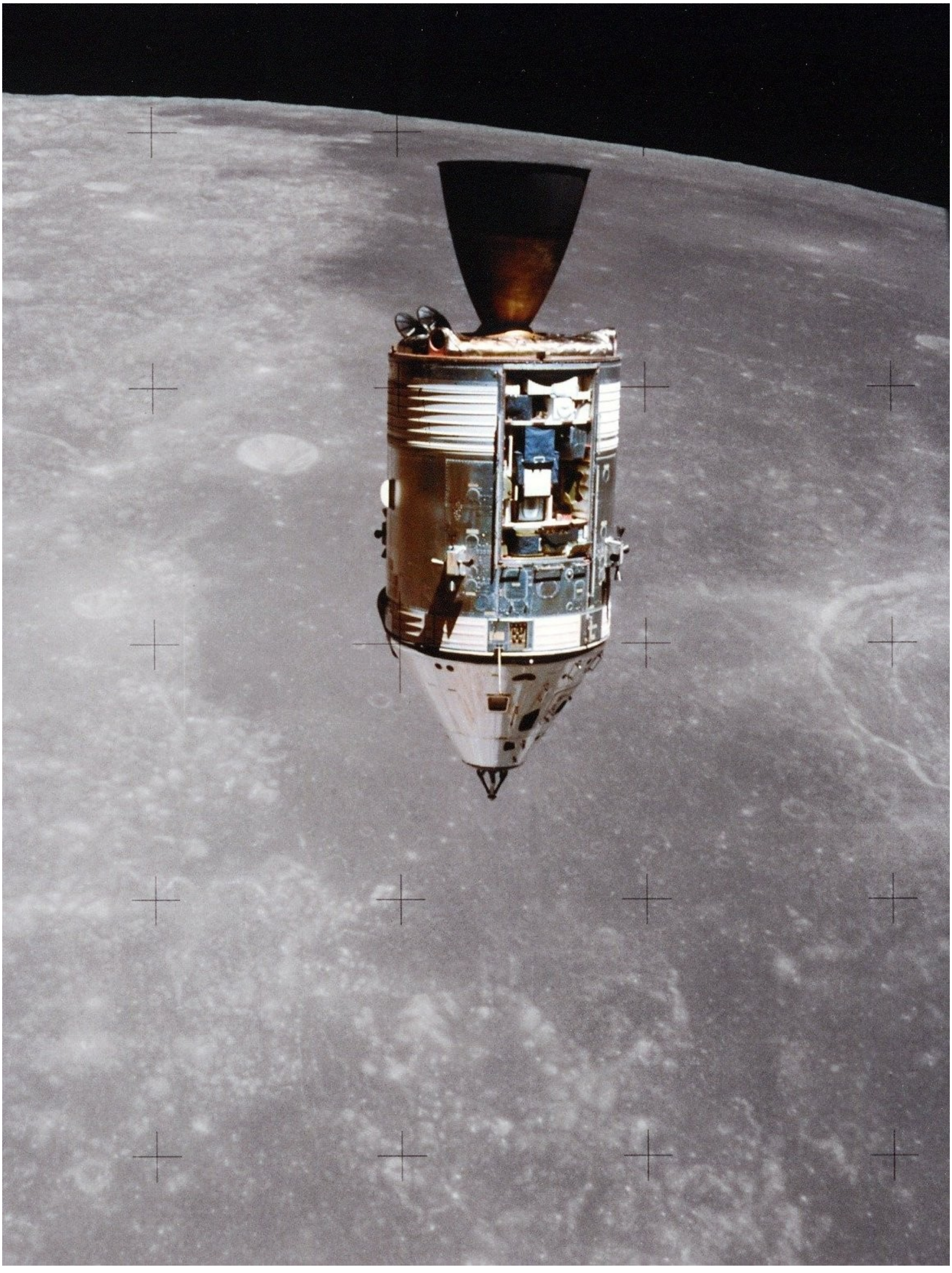


Background:

Launch of Apollo 15 onboard a Saturn V SA-510 launch vehicle,

Kennedy Space Center, Florida, U.S., July 26, 1971 (image NASA, public domain)



AS15-88-11972 (30 July 1971)

A view of the Apollo 15 CSM in lunar orbit as photographed from the Lunar Module (LM) just after rendezvous. The lunar nearside is in the background. We can easily distinguish the SIM bay and the X-ray spectrometer, the first white rectangular instrument near the SPS engine. (image NASA, public domain)