Recovery, Restoration and Archiving of Previously Lost Data and Metadata from the Apollo Lunar Surface Experiments Package (ALSEP)

S. Nagihara[1], D. R. Williams[2], Y. Nakamura[3], W. S. Kiefer[4], S. A. McLaughlin[2,5], and, P. T. Taylor[2]

1: Department of Geosciences, Texas Tech University, Lubbock, Texas 79409

2: Goddard Space Flight Center, Greenbelt, Maryland 20771

3: Institute for Geophysics, University of Texas at Austin, Austin, Texas 78758

4: Lunar and Planetary Institute, Universities Space Research Association, Houston, Texas 77058

5: Telophase Corporation, Alexandria, Virginia 22201

Abstract

The Apollo Lunar Surface Experiments Package (ALSEP) is the name used to collectively represent the geophysical instruments deployed on the lunar surface by the astronauts on Apollo 12, 14, 15, 16, and 17. These instruments were active from the times of their deployment (November 1969 – December 1972) to September 1977. During that time, fourteen types of experiments were conducted, and their data were transmitted to Earth. The experiment PIs processed them. At the conclusion of the experiments, some of these data were submitted to the NASA Space Science Data Coordinated Archive (NSSDCA) for archiving, while others were not. The raw instrument data received from the Moon prior to March 1976 were not archived, either. The unarchived data, resided on open-reel magnetic tapes, became lost in the decades since, along with much of the metadata (the information necessary/useful in properly processing/analyzing the data). This article retraces the history of the ALSEP data archiving efforts in the 1970s, the subsequent loss of the data tapes, and the search, recovery, and restoration of the lost data by contemporary researchers in the 21st century. In 2006, NSSDCA began reformatting some of the ALSEP data archived in the 1970s to conform with the current Planetary Data System (PDS). In 2010, 440 of the previously lost magnetic tapes containing the raw ALSEP data were recovered. From these tapes, the data were extracted, re-packaged for individual experiments, and, for those with sufficient metadata, processed into higher order data readily usable by researchers. All of these data products have been recently archived with either PDS or NSSDCA. These newly restored data fill a number of gaps in the previously existing archive of the ALSEP data. In addition, tens of thousands of pages of Apollo era documents have been optically scanned and compiled into an online searchable catalog. This article also describes the content, organization, and usage of the restored raw ALSEP data and metadata.

1 Introduction

When Apollo 11 landed on the Moon in July 1969 (Fig. 1), astronauts Neil Armstrong and Edwin Aldrin set up geophysical experiments by deploying the instruments that were collectively called the Early Apollo Scientific Experiments Package (EASEP). The package consisted of a seismometer, a laser-ranging retro-reflector, an instrument for measuring the noble gas composition of the solar wind, and a dust detector (Bates et al., 1969; Hess and Calio, 1969). Being solar powered, the EASEP instruments lasted only 21 earth-days, except for the retro-reflector, which did not require power.

Starting on Apollo 12, the astronauts deployed a more expansive array of instruments, powered by a radioisotope thermoelectric generator (RTG). Those deployed on Apollo 12, 14, 15, 16, and 17 (Fig. 1) were called the Apollo Lunar Surface Experiments Package (ALSEP). Each ALSEP station consisted of a mix of 5 to 8 instruments (Table 1). Most of these instruments lasted well beyond their expected lives. When NASA terminated the entire ALSEP program in September 30, 1977, one to three instruments were still operating at each of the 5 stations on the Moon (Fig. 2).

The ALSEP program occupies a unique place in the history of planetary science. For nearly 5 years in the 1970s, a network of 5 geophysical observatories, distributed across the near side of the Moon (Fig. 1), each consisting of an array of multiple instruments, simultaneously and continuously transmitted data to the Earth. An experiment of such a scope has never been repeated since on the Moon or any other extraterrestrial body.

In the years that followed the Apollo missions, the data from the ALSEP stations, along with the rock samples returned by the astronauts, dramatically improved our understanding of the Moon's surface environment, interior, and geologic evolution. To this day, the ALSEP data continue to yield new findings, as researchers apply new analytical techniques (e.g., Weber et al, 2010). Especially in the last decade, international science communities have re-focused on the Moon, and a large number of contemporary researchers are now examining the ALSEP data.

One of the challenges for contemporary ALSEP researchers has been that large portions of the experimental data received from the Moon were never archived with the NASA Space Science Data Coordinated Archive (NSSDCA), formerly the National Space Science Data Center (NSSDC). At the conclusion of the Apollo program, thousands of open-reel magnetic tapes containing ALSEP data were scattered in various locations. Most of these tapes have been lost in the decades since. In the following section, we provide a more detailed narrative on the ALSEP data recording and archiving activities in the 1970s.

In year 2010, a group of researchers, including the authors of the present study, founded the ALSEP Data Recovery Focus Group, based at NASA's Lunar Science Institute (currently Solar System Exploration Virtual Research Institute, SSERVI). The group's primary missions were to search and restore the previously unarchived ALSEP data, and to make them available to contemporary lunar researchers. This article describes the newly restored ALSEP data and their archival brought about by the activities of this group.

When the ALSEP program concluded in 1977, the metadata, such as the timeline of the individual experiments, the bit-level organization of the raw data received from the Moon, the data reduction methods, etc. had been described in reports and memos by the investigators directly involved (Table 1), but few of these details were published in major scientific journals. Contemporary researchers have had difficulty locating these documents. The ALSEP Data Recovery Focus Group has searched them, made digital copies of the documents found, and made them available through the worldwide web portals of the Lunar and Planetary Institute. This article also describes some of these key documents that are particularly useful for contemporary researchers.

Table 1. A list of EASEP/ALSEP experiments

Experiment	**Acronym**	**PI**	**A11**	**A12**	**A14**	**A15**	**A16**	**A17**
Active Seismic	ASE	R. Kovach			X		X	
Charged Particle Lunar Environment	CPLEE	B. O'Brien D. Reasoner[1]			X			
Cold Cathode Gage	CCGE	F. Johnson[1]		X	X	X		
Dust Thermal and Radiation Engineering Measurement[2]	DTREM	B. O'Brien J. Bates	X	X	X	X		
Heat Flow Experiment	HFE	M. Langseth[1]				X	X[4]	X
Lunar Ejecta and Meteorites	LEAM	O. Berg						X
Lunar Atmospheric Composition Experiment[3]	LACE	J. Hoffman						X
Laser Ranging Retroreflector	LRRR	J. Faller	X		X	X		
Lunar Seismic Profiling	LSPE	R. Kovach						X
Lunar Surface Gravimeter	LSG	J. Weber[1]						X
Lunar Surface Magnetometer	LSM	C. Sonnet[1] P. Dyal[1]		X		X	X	
Passive Seismic	PSE	G. Latham	X	X	X	X	X	
Solar Wind Spectrometer	SWS	C. Snyder		X		X		
Suprathermal Ion Detector	SIDE	J. Freeman[1]		X	X	X		

1: Deceased, 2: It is also known as the Dust Detector Experiment (DDE), 3: It is also known as the Lunar Mass Spectrometer (LMS), , 4: The astronauts were not able to deploy the instrument successfully.

2 A Summary of the ALSEP Experiments

Sullivan (1994) discussed how each of the ALSEP experiments was deployed and operated, and Bates et al. (1979) provided a summary of results during the first 8 years of ALSEP data analysis. Here, we provide a brief description of each experiment and, where appropriate, of recent experiment results in order to document the importance of our data recovery efforts. However, a comprehensive review of all ALSEP experiment publications is beyond the scope of the current paper.

The various ALSEP experiments can be broadly divided into two groups. One group of experiments focused on the internal structure of the Moon. The Passive Seismic Experiment (PSE) included both a single-axis (vertical) short period seismometer and a three-axis long period seismometer, and the four-station network (Apollos 12, 14, 15, and 16) detected more than 12,000 lunar seismic events between 1969 and 1977. Modern computer processing methods have led to a resurgence of new PSE analyses, including detections of new clusters of deep seismic events (Nakamura, 2003, 2005), the seismic velocity structure of the lunar crust and mantle (Gagnepain-Beyneix et al., 2006; Garcia et al., 2011; Khan et al., 2013), and the size and physical state of the lunar core (Weber et al., 2011). The Active Seismic Experiment (ASE) and Lunar Seismic Profiling Experiment (LSPE) used networks of geophones and small explosive charges to probe the shallow structure of the lunar regolith and crust. ASE data covers the upper ~200 meters of the regolith at the Apollo 14 and 16 landing sites, and LSPE data covers the crust to a depth of ~3 km at the Apollo 17 landing site (Cooper et al., 1974). The Lunar Surface Gravimeter (LSG) was originally intended to make high precision measurements of the time variability of lunar gravity in an attempt to measure gravity waves. Although unsuccessful for this purpose, it was recently shown that the LSG can also be used as a short-period seismometer, facilitating the recognition of 5 new clusters of deep moonquakes (Kawamura et al., 2015). The Laser Ranging Retroreflector (LRRR) uses laser time of flight measurements from terrestrial telescopes to measure how the Moon’s distance from Earth varies with time due to tides. Because this requires no power on the Moon, LRRR is the only ALSEP experiment that is still in operation. LRRR results constrain the

Moon's deep internal structure and also provide sensitive tests of some predictions of Einstein's theory of general relativity (Williams et al., 2006; Williams and Boggs, 2015). In recent years, combined analyses of Apollo PSE and LRRR data in combination with orbital gravity measurements from NASA's GRAIL mission have substantially improved our overall knowledge of the Moon's deep interior structure (Williams et al., 2014; Matsuyama et al., 2016). The Heat Flow Experiment (HFE) determined the outward flow of the endogenic heat of the Moon by measuring the thermal gradient and the thermal conductivity of the subsurface regolith down to the depth unaffected by insolation (1.5 to 2.4 m) at the Apollo 15 and 17 sites (Langseth, 1977; Grott et al., 2011). The data revealed that heat flow is greater at Apollo 15 (21 mW/m^2) than at Apollo 17 (16 mW/m^2). The higher heat flow of the former was later attributed to the higher abundance of Thorium on the surface of the Procellarum KREEP Terrain in which the site is located (Wieczorek and Phillips, 2000). The Lunar Surface Magnetometer (LSM) measured the temporal variability of the magnetic field at the surface of the Moon. One important early result was an upper bound on the size of the lunar core, $r_{core} \leq 360$ km (Hood et al., 1982), although this has been superseded by later orbital measurements (Shimizu et al., 2013). LSM data also measured the interaction between the Moon and the solar plasma environment.

The second group of experiments focused on the surface environment of the Moon, including its atmosphere, dust, and solar charged particles. The Cold Cathode Gauge Experiment (CCGE) and the Lunar Atmospheric Composition Experiment (LACE) both measured the tenuous lunar atmosphere. CCGE measured the time variability of atmospheric pressure, and LACE used a mass spectrometer to measure the atmospheric composition over the range 1 to 110 amu, including He, Ar, and possibly Ne (Morgan and Shemansky, 1991). Several ALSEP instruments measured the energy and flux of charged particles over various energy ranges. The Suprathermal

Ion Detector Experiment (SIDE) measured the energy and mass spectra of positive ions near the lunar surface with energies of up to 3500 eV (Bates et al., 1979). In addition to measuring charged particles associated with the solar wind, SIDE also detected a large water release event believed to be associated with the Apollo 14 Lunar Module on the first sunrise following the Apollo 14 landing (Freeman and Hills, 1991). The Solar Wind Spectrometer (SWS) measured the flow direction and energies of both electrons and protons in the solar wind at energies up to 1330 eV for electrons and 9780 eV for protons (Bates et al., 1979). The Charged Particle Lunar Environment Experiment (CPLEE) measured the fluxes of both positively and negatively charged particles with energies of up to 50,000 eV (Bates et al., 1979). The Dust, Thermal and Radiation Engineering Measurement (DTREM) was an engineering sensor that measured the accumulation of lunar dust on the ALSEP, as summarized by O'Brien (2011), it also characterized the temperature and radiation environment. The Lunar Ejecta and Meteorites (LEAM) experiment was originally intended to measure the speed, direction, and energy of micrometeorites impacting the lunar surface, although in practice it is thought that LEAM mostly measured the transport of lunar dust (Colwell et al., 2007; Grün and Horányi, 2013).

3 Timeline Narrative of the ALSEP Data Recording, Archiving, and Related Activities in the 1970s

In reconstructing the timeline of the ALSEP operation after Apollo 17, particularly the data archiving effort, the present authors performed extensive searches and reviews of documents generated during the Apollo era. Most of these documents were found at the Lunar and Planetary Institute (LPI) in Houston, Texas, the National Archives facility in Fort Worth, Texas, and the

Records Offices of the NASA Headquarters, Johnson Space Center (JSC), and Goddard Space Flight Center (GSFC). NASA Technical Reports Server (ntrs.nasa.gov) has also been searched. In addition, the present authors have interviewed some of the people who were involved in the ALSEP operation in the 1970s.

Bates et al. (1979) provides concise summaries of the timelines and the key events for the individual ALSEP experiments. From November 20, 1969 to April 5, 1973, daily status reports on the ALSEP stations were generated at JSC. From April 1973 to September 1977, weekly logs were compiled. These logs have been bound annually as the ALSEP Status Reports (1971-1973) and the ALSEP Performance Summary Reports (1973-1977), and their digital copies are now available through the web portal of the LPI (https://www.lpi.usra.edu/lunar/documents/).

In December 1972, when the Apollo 17 astronauts returned to Earth, five ALSEP stations were operational on the Moon. Table 1 lists the instruments deployed at these stations. Figure 2 shows the periods in which they were operational. Some of the ALSEP instruments are referenced by the experiments for which they were used. The laser-ranging retro-reflectors (LRRRs) were used for earth-based time-of-flight observations. The present study focuses on the in-situ experiments that collected data on the lunar surface and transmitted them to Earth.

Data from the five ALSEP stations were received by the Manned Space Flight Network (MSFN) stations. There, the data were recorded on 7- and 14-track, analog, open-reel magnetic tapes. These tapes were called ‘range tapes’ (Lockheed Electronics Company, 1974). The transmitted signals were pulse-code modulated (PCM), and thus the information content was 7-track digital, even though it was recorded on the analog tapes. The range tapes were sent to JSC. There, the data were sorted for the individual experiments, recorded them on digital open-reel magnetic tapes, and sent to the principal investigators (PIs) of the experiments for their use ('PI tapes').

In April 1973, JSC began to generate tapes specifically for archiving the raw ALSEP data received from the Moon. One earth-day worth of data from all the instruments for each ALSEP station were recorded on a 7-track digital, open-reel magnetic tape (Lockheed Electronics Company, 1975). These tapes were called 'ARCSAV tapes' or '24-hour time-edited tapes' (Fig. 3). Five ARCSAV tapes were generated every day at JSC.

By mid-1975, NASA had terminated data analysis contracts with the ALSEP experiment PIs, except for the Passive Seismic Experiment (PSE), while JSC continued recording the data from the all ALSEP instruments on ARCSAV tapes.

In March 1976, the Geophysics Laboratory of the University of Texas at Austin, located in Galveston, Texas, took over the work of generating archival tapes of the raw ALSEP data. The data were recorded on 9-track, digital open-reel magnetic tapes. These tapes were called 'work tapes'. The generation of the work tapes continued until the conclusion of the ALSEP program in September 1977 (Fig. 3).

When the ALSEP program was terminated, the Geophysical Data Evaluation Working Group, assembled by the JSC management in the late 1972 (Eichelman and Toksöz, 1973), made recommendations on data archiving. The working group consisted of researchers from academia, aerospace industry, and the NASA research centers. The group concluded that 'NASA should store, for use by other scientists, only data reduced and corrected by the PI' and that 'it would be neither practical or desirable, in most cases, to distribute raw data from the range tapes' (Bates et al., 1979). Some of the PIs by that time delivered the data they analyzed to NSSDCA. Bates et al. (1979) lists the datasets submitted by the PIs then. These datasets came in various forms and different stages of processing. In some cases, the PIs did not process the entire data they received; they worked on only the portions of the data they were interested in and submitted them to NSSDCA. In some other cases, the data were turned in only on paper or microfilms with limited supporting documents. In addition, for those experiments whose PI contracts ended prior to mid-1975, the data collected in the final 2 to 3 years were left unprocessed and unarchived.

4 Post-Apollo Era Loss of the ALSEP Raw Data Tapes and the 21st Century Search and Recovery Efforts

At the conclusion of the ALSEP program in 1977, thousands of magnetic tapes containing raw instrument data existed at various locations. Since the decision was made not to archive the raw data, many of these tapes have been lost in the decades since. The people involved in the ALSEP operation have long been retired or passed away, and their knowledge on whereabouts of the archival tapes was not passed on to the current generation. Here we summarize the fates of these magnetic tapes as we have learned through our investigation in the last decade.

Most of the range tapes were recycled at GSFC. Two reports (Lockheed Electric Company, 1975; Bates et al., 1979) mention that the range tapes made prior to April 1973 were kept for archiving, but these reports differ on where these tapes had been sent/kept. We searched those locations, but did not find the tapes.

JSC produced over 5000 ARCSAV tapes from April 1973 to February 1976. Our document search at the JSC Records Office revealed that most of these tapes had been sent to the Washington National Records Center (WNRC) in Suitland, Maryland in 1975 and 1976 in several batches. In 2010, we confirmed that 440 ARCSAV tapes from April through June of 1975 were still kept at

WNRC. The records also showed that the rest of the ARCSAV tapes had been withdrawn, presumably by someone at JSC, in the early 1980s. Our paper trail ended there. A recent search conducted at JSC did not find any more ARCSAV tapes.

The University of Texas generated the work tapes in March 1976 through September 1977. The work tapes were preserved at the Institute for Geophysics of the university. The files on these tapes were copied to cassette tapes in the early 1990s. In 2017, digital contents of the full set of these tapes were delivered to and archived at NSSDCA as collection PSPG-00739.

The experiment PIs had possession of the PI tapes at their home institutions, but few of these tapes were send to NSSDCA for archival purposes at the conclusion of the ALSEP program. Some years later, however, the PSE investigators were able archive the contents of their PI tapes with the Data Management Center of the Incorporated Research Institutions Seismology, through which NSSDCA obtained a copy in 2017. For the other experiments, it is likely that the PI tapes were disposed of either by the PIs themselves or the institutions where they were based, after their retirement.

In 2006, NSSDCA commenced the Lunar Data Project (Williams et al., 2006). Under this project, ALSEP data submitted by the experiment PIs in analog forms (paper, microfilms, etc.) have been digitized and reformatted into ASCII conformable to the Planetary Data System (PDS) (Fig. 2). Some of the PI-submitted data in binary forms on tapes have also been reformatted for archival with PDS.

In 2013 through 2017, we hired companies specialized in data restoration from old magnetic tapes, and extracted files from the 440 ARCSAV tapes recovered from WNRC in 2010. These files have been archived at NSSDCA (Fig. 3). More detailed description on these raw data are given in the following section.

Also in the last decade, the ALSEP Data Recover Focus Group members have made digital copies of the ALSEP-related documents and metadata that were stored at LPI and the National Archives of Fort Worth, Texas. Currently, PDF copies of a total of ~840 documents (56,000+ pages) are now available at LPI's web portal on ALSEP documents (https://repository.hou.usra.edu/handle/20.500.11753/2).

5 Description and Processing of the Raw ALSEP Data

In the current state of ALSEP data availability (Fig. 2), most of the experiments have periods for which only the raw data are available, especially in 1975 through 1977. Therefore, it is advisable for contemporary researchers to familiarize themselves with the raw data. Here, we briefly describe the organization of the raw ALSEP data sets.

The raw ALSEP data recorded on the ARCSAV and work tapes are organized in the chronological order, and packets from the various instruments are intermeshed. Lockheed Electric Company (1975) describes the bit-level organization of the raw data. In its terminology, an 'ALSEP frame' refers to one cycle of data transmission from one ALSEP station. One earth-day worth of raw data consisted of 143,100 ALSEP frames. Each ALSEP frame consisted of data packets from all the instruments located at that station, logged over a nominal period of ~603.77 milliseconds. The data packets from the individual instruments that made up the ALSEP frame were called 'ALSEP words'. Each ALSEP word was 10-bit long, followed by 2 null bits.

One ALSEP frame consisted of 64 ALSEP words. Depending on the data rate required, different numbers of ALSEP words were allocated to the individual experiments within the ALSEP frame. For example, at the Apollo 12, 14, 15, and 16 sites, the PSE, requiring high sampling rates, used 47 to 49 ALSEP words in one ALSEP frame, and the other instruments shared the remaining 15 to 17 ALSEP words. For those non-seismic experiments, each ALSEP word represented the output of one of the sensor channels of that instrument. For example, at the Apollo 15 and 17 sites, the heat flow experiment (HFE) used only one ALSEP word in each ALSEP frame. Transmission of a full scan of the HFE output channels required 720 frames. Therefore, the sampling interval for the HFE sensors was ~7.25 minutes (0.604 sec. x 720).

In the course of restoring and archiving the ALSEP data, we have classified them in three levels of processing (Table 2). The Level-0 data are the binary files as extracted from the ARCSAV and work tapes. Because the ARCSAV tapes have been degraded in the last 40+ years, the Level-0 data contain a considerable number of bit errors. We have been able to recognize these errors, partly because we know the exact bit-level organization of the raw data (Lockheed Electric Company, 1975). Using this information, we have corrected most of these bit errors, one tape file at a time, and produced cleaned Level-0 data sets ('Level-0a'). Both Level-0 and Level-0a data sets have been archived with NSSDCA.

Level-1 data (Table 2) are raw data sets for the individual experiments, extracted from the Level-0a sets and repackaged. Level-1b products are in the original binary format, and they are somewhat equivalent to the PI tape files. Level-1a products are the raw data in ASCII and currently being archived with PDS.

Level-2 data (Table 2) are fully processed data that can be readily scientifically analyzed. The 'reduced data' archived by the PIs in the 1970s are considered Level 2. We have been successful in processing Level-1 data into Level 2 for a few of the instruments. The Level-2 processing requires knowledge of the data reduction method and the calibration data used by the PI of that experiment. In the following section, we describe the sources of these required metadata.

Table 2 Definition/description of the ALSEP data products according to the level of data processing.

Data **Product**	**Description**
Level 0	Raw binary files extracted from the ARCSAV tapes or the work tapes without any modification.
Level 0a	Level 0 data quality-controlled for obvious bit errors resulting from tape-reading errors and data transmission errors (from the Moon to the MSFN stations).
Level 1b	Individual ALSEP experiments, extracted from Level-0a binary files.
Level 1a	Individual ALSEP experiments, Level-1b files converted to ASCII for archiving with PDS
Level 2	Individual experimental data fully processed (or translated) into scientifically meaningful numbers.

6 The ALSEP Metadata and Other Useful Documents

For researchers interested in the individual ALSEP experiments, Lauderdale and Eichelman (1974) outlines the purpose of each experiment, the instrument designs, the instrument layout at the landing sites, and the data reduction methodologies used by the PIs. In addition, the Apollo Preliminary Science Reports (PSRs), published for each Apollo mission, provide similar technical information and preliminary data analysis by the PIs. PDF copies of the PSRs can be downloaded at https://www.hq.nasa.gov/alsj/alsj-psrs.html.

For the individual ALSEP experiments, most of the PIs published their scientific findings in peer-reviewed journals, which can easily be searched by contemporary researchers. However, few of them describe the experiments themselves and their data reduction methods with enough details for other researchers to be able to independently reprocess or reanalyze the data. Through our document search and recovery efforts, we have learned that, at least for some of these experiments, the PIs gave more detailed technical information in the papers they presented in conferences and their reports to NASA. In particular, the PIs' final reports provide a more comprehensive description of the experiments, the analytical methodology, and the key findings than their articles in major journals (e.g., Hoffman, 1976; Kovach and Watkins, 1976; Giganti et al., 1977; Langseth, 1977). The final reports we have been able to locate are now available through LPI's ALSEP web portal.

For technical information on the ALSEP instruments, researchers may also want to consult the collection of documents called 'Acceptance Data Package' (ADP)'. The ADP reports were generated by the companies contracted by NASA to design and fabricate the ALSEP instruments. These reports described the hardware design, the laboratory tests performed on them, the test data, and the test data analyses for each of the flight models and the system qualification models. The ADP reports are currently stored at the National Archives of Fort Worth. In our rough estimation, the ADP reports exceed 100,000 pages in total. The reports' contents and their level of detail vary among the different ALSEP experiments. For some of the experiments, the ADP reports are the only surviving sources of the metadata necessary for Level-2 data processing. For example, Nagihara et al. (2018) restored major portions of the previously unarchived HFE data from 1975 through 1977 by processing Level-1a raw data and using the instrument calibration data reported in the ADP reports (e.g., Arthur D. Little, Inc., 1968). Some excerpts of the ADP reports are available through the LPI's ALSEP web portal.

In utilizing the ADP reports, however, researchers should be aware that, because these reports were written pre-flight, they never mention which of these flight models actually flew on which of the Apollo missions. In deciding which flight model flew on the Apollo mission of their interest, researchers would need to examine other memos and reports by the PIs and the hardware provider (e.g., BENDIX Corporation, 1973).

7 Conclusion

Fifty years after the first human landing on the Moon, the ALSEP program remains to be the only geophysical experiments conducted on the lunar surface. More than a dozen instruments, stationed at five of the Apollo landing sites, continuously transmitted data for nearly 5 to 8 years. When the ALSEP program was terminated in 1977, the Geophysical Data Evaluation Working Group made the fateful decision not to archive the raw instrument data, even though the reduced/processed datasets submitted to NSSDCA were far from complete. There is a lesson to be learned here. Perhaps the decision makers did not realize the long-lasting scientific return from the data. In addition, they probably never expected that no more data could be gathered on the lunar surface for a half century.

Contemporary researchers have renewed their interests in the Moon in the last decade. China landed a robotic spacecraft on the Moon this year. More robotic and human missions to land on the Moon are being planned within the next decade. As scientists formulate experiments to be conducted on these future missions (e.g., Lunar Exploration Analysis Group, 2017), they still look to the ALSEP data and metadata for guidance. The SSERVI ALSEP Focus Group was founded to help these researchers by recovering the previously lost ALSEP data and making them available. We have recovered the 440 original archival tapes containing raw data from April through June of 1975, extracted data from them, and archived them with NSSDCA and PDS. We have also established a digital, searchable metadata archive at LPI. The key websites for locating the recovered ALSEP data are https://pds-geosciences.wustl.edu/missions/apollo/index.htm, which is the NSSDCA/PDS website that archives the datasets, and https://repository.hou.usra.edu/handle/20.500.11753/2, which houses the metadata files. While some of these recently restored data have already resulted in new scientific findings (Nagihara et al., 2018; Weber et al., 2018), the group's effort for searching and recovering more of the missing data continues.

8 Acknowledgments

The work presented here received financial support from the Lunar Advanced Science and Exploration Research (NNX13AD47G) and the Planetary Data Archiving, Restoration, and Tools (NNX15AI82G) programs of NASA's Science Mission Directorate. The Lunar and Planetary Institute is operated for NASA under Cooperative Agreement NNX15AL12A. In recovering the original ALSEP archival data tapes and related documents, we received assistance from the National Archive of Fort Worth, the Washington National Records Center, and the Records Offices of the NASA Headquarters, Johnson Space Center, and Goddard Space Flight Center.

References

Arthur D. Little, I., 1968. Heat Flow Probe program: Case 72957-02, acceptance data package, Flight Model 4 (S/N 7) [excerpt], p. 123. https://repository.hou.usra.edu/handle/20.500.11753/710

Bates, J.R., Freden, S.C., O'Brien, B.J., 1969. The modified dust detector in the Early Apollo Scientific Experiments Package. Apollo 11 Preliminary Science Report NASA SP-214, 199-201.

Bates, J. R., Lauderdale, W. W., Kernaghan, H., 1979. ALSEP Termination Report. NASA Reference Publication 1036, Washington, DC, pp. 165. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19790014808.pdf

Bendix Aerospace Systems Division, 1973. Final report for ALSEP Arrays A, B, C. and A-1. pp. 264. https://repository.hou.usra.edu/handle/20.500.11753/713

Colwell, J.E., Batiste, S., Horányi, M., Robertson, S., Sture, S., 2007. Lunar surface: Dust dynamics and regolith mechanics. Reviews of Geophysics 45, RG2006, doi:10.1029/2005RG000184.

Eichelman, W.F., Toksoz, M.N., 1973. Apollo lunar surface data archiving report of the Geophysical Data Evaluation Working Group, p. 97. https://www.lpi.usra.edu/lunar/ALSEP/pdf/31111000673978.pdf

Freeman Jr., J.W., Hills, H.K., 1991. The Apollo lunar surface water vapor event revisited. Geophysical Research Letters 18, 2109-2112.

Gagnepain-Beyneix, J., Lognonné, P., Chenet, H., Lombardi, D., Spohn, T., 2006. A seismic model of the lunar mantle and constraints on temperature and mineralogy. Physics of the Earth and Planetary Interiors 159, 140-166.

Garcia, R.F., Gagnepain-Beyneix, J., Chevrot, S., Lognonné, P., 2011. Very preliminary reference Moon model. Physics of the Earth and Planetary Interiors 188, 96-113.

Giganti, J.J., Larson, J.V., Richard, J.P., Tobias, R.L., Weber, J., 1977. Lunar surface gravimeter experiment: final report. University of Maryland, p. 26.

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19770012037.pdf

Grott, M., Knollenberg, J., Krause, C., 2010. Apollo lunar heat flow experiment revisited: A critical reassessment of the in situ thermal conductivity determination. Journal of Geophysical Research: Planets 115, E11005, doi:10.1029, 2010JE003612.

Grün, E., Horányi, M., 2013. A new look at Apollo 17 LEAM data: Nighttime dust activity in 1976. Planetary and Space Science 89, 2-14.

Hare, T.M., Keszthelyi, L., Gaddis, L.R., 2014. Online Planetary Data and Services at USGS Astrogeology, 45th Lunar and Planetary Science Conference. Lunar and Planetary Institute, Houston, Abstract #2487.

Hess, W.N., Calio, A.J., 1969. Summary of scientific results. Apollo 11 Preliminary Science Report NASA SP-214, 1-9.

Hoffman, J.H., 1976. Lunar atmospheric composition experiment: final report. University of Texas at Dallas, p. 132.

https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19760025001.pdf

Hood, L.L., Herbert, F., Sonett, C.P., 1982. The deep lunar electrical conductivity profile: Structural and thermal inferences. Journal of Geophysical Research: Solid Earth 87, 5311-5326.

Kawamura, T., Kobayashi, N., Tanaka, S., Lognonné, P., 2015. Lunar Surface Gravimeter as a lunar seismometer: Investigation of a new source of seismic information on the Moon. Journal of Geophysical Research: Planets 120, 343-358.

Khan, A., Pommier, A., Neumann, G. A., & Mosegaard, K. (2013). The lunar moho and the internal structure of the Moon: A geophysical perspective. *Tectonophys*. 69, 331-352.

Kovach, R.L., Watkins, J.S., 1976. Apollo 14 and 16 active seismic experiments and Apollo 17 lunar seismic profiling: final report. Stanford University, p. 165. https://repository.hou.usra.edu/handle/20.500.11753/822

Kovach, R.L., Watkins, J.S., 1973. The velocity structure of the lunar crust. The Moon 7, 63-75.

Langseth, M.G., Jr., 1977. Lunar Heat-flow Experiment: Final Technical Report. Lamont-Doherty Geological Observatory, Palisades, NY, CU-4-77, p. 289. https://repository.hou.usra.edu/handle/20.500.11753/855

Lauderdale, W.W., Eichelman, W.F., 1974. Apollo Scientific Experiments Data Handbook. Johnson Space Center, Houston, NASA TM X-58131, p. 1011. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19760007062.pdf

Lockheed Electric Company, 1975. Apollo Lunar Surface Experiment Package Archive Tape Description Document. Johnson Space Center, Houston, TX, JSC-09652, p. 319. https://repository.hou.usra.edu/handle/20.500.11753/42

Lockheed Electric Company., 1974. Data processing procedure for ALSEP production. Lockheed Electronics Company, LEC-1191, p. 73. https://repository.hou.usra.edu/handle/20.500.11753/39

Lunar Exploration Analysis Group, 2017, Advancing Science of the Moon, Report of the Special Action Team, p. 69, https://www.lpi.usra.edu/leag/reports/ASM-SAT-Report-final.pdf

Matsuyama, I., Nimmo, F., Keane, J.T., Chan, N.H., Taylor, G.J., Wieczorek, M.A., Kiefer, W.S., Williams, J.G., 2016. GRAIL, LLR, and LOLA constraints on the interior structure of the Moon. Geophysical Research Letters 43, 8365-8375.

Morgan, T.H., Shemansky, D.E., 1991. Limits to the lunar atmosphere. Journal of Geophysical Research: Space Physics 96, 1351-1367.

Nagihara, S., Kiefer, W.S., Taylor, P.T., Williams, D.R., Nakamura, Y., 2018. Examination of the Long-Term Subsurface Warming Observed at the Apollo 15 and 17 Sites Utilizing the Newly Restored Heat Flow Experiment Data From 1975 to 1977. Journal of Geophysical Research: Planets 123, 1125-1139.

Nakamura, Y., 2003. New identification of deep moonquakes in the Apollo lunar seismic data. Physics of the Earth and Planetary Interiors 139, 197-205.

Nakamura, Y., 2005. Farside deep moonquakes and deep interior of the Moon. Journal of Geophysical Research: Planets 110, E01001.

Nakamura, Y., 2011. Timing problem with the Lunar Module impact data as recorded by the LSPE and corrected near-surface structure at the Apollo 17 landing site. Journal of Geophysical Research: Planets 116, E12005.

O'Brien, B.J., 2011. Review of measurements of dust movements on the Moon during Apollo. Planetary and Space Science 59, 1708-1726.

Shimizu, H., Matsushima, M., Takahashi, F., Shibuya, H., Tsunakawa, H., 2013. Constraint on the lunar core size from electromagnetic sounding based on magnetic field observations by an orbiting satellite. Icarus 222, 32-43.

Sullivan, T.A., 1994. Catalog of Apollo Experiment Operations, NASA Reference Publication 1317, p. 162.

https://repository.hou.usra.edu/handle/20.500.11753/15.

Weber, R.C., Dimech, J.-L., Phillips, D., Molaro, J., Schmerr, N.C., Fassett, C., 2018. Thermal Moonquakes: Implications for Surface Properties, 49th Lunar and Planetary Science Conference. Lunar and Planetary Institute, Houston, p. Abstract #1497.

Weber, R.C., Lin, P.Y., Garnero, E.J., Williams, Q., Longnonne, P., 2011. Seismic detection of the lunar core. Science 331, 309-312.

Wieczorek, M.A., Phillips, R.J., 2000. The "Procellarum KREEP Terrane": Implications for mare volcanism and lunar evolution. Journal of Geophysical Research: Planets 105, 20417-20430.

Williams, D.R., Grayzeck, E.J.J., 2006. The Lunar Data Project — Restoration of Apollo Data for Future Lunar Exploration, 37th Lunar and Planetary Science Conference. Lunar and Planetary Institute, Houston, p. Abstract #1187.

Williams, J.G., Turyshev, S.G., Boggs, D.H., Ratcliff, J.T., 2006. Lunar laser ranging science: Gravitational physics and lunar interior and geodesy. Advances in Space Research 37, 67-71.

Williams, J.G., Konopliv, A.S., Boggs, D.H., Park, R.S., Yuan, D.-N., Lemoine, F.G., Goossens, S., Mazarico, E., Nimmo, F., Weber, R.C., Asmar, S.W., Melosh, H.J., Neumann, G.A., Phillips, R.J., Smith, D.E., Solomon, S.C., Watkins, M.M., Wieczorek, M.A., Andrews-Hanna, J.C., Head, J.W., Kiefer, W.S., Matsuyama, I., McGovern, P.J., Taylor, G.J., Zuber, M.T., 2014. Lunar interior properties from the GRAIL mission. Journal of Geophysical Research: Planets 119, 1546-1578.

Williams, J.G., Boggs, D.H., 2015. Tides on the Moon: Theory and determination of dissipation. Journal of Geophysical Research: Planets 120, 689-724.

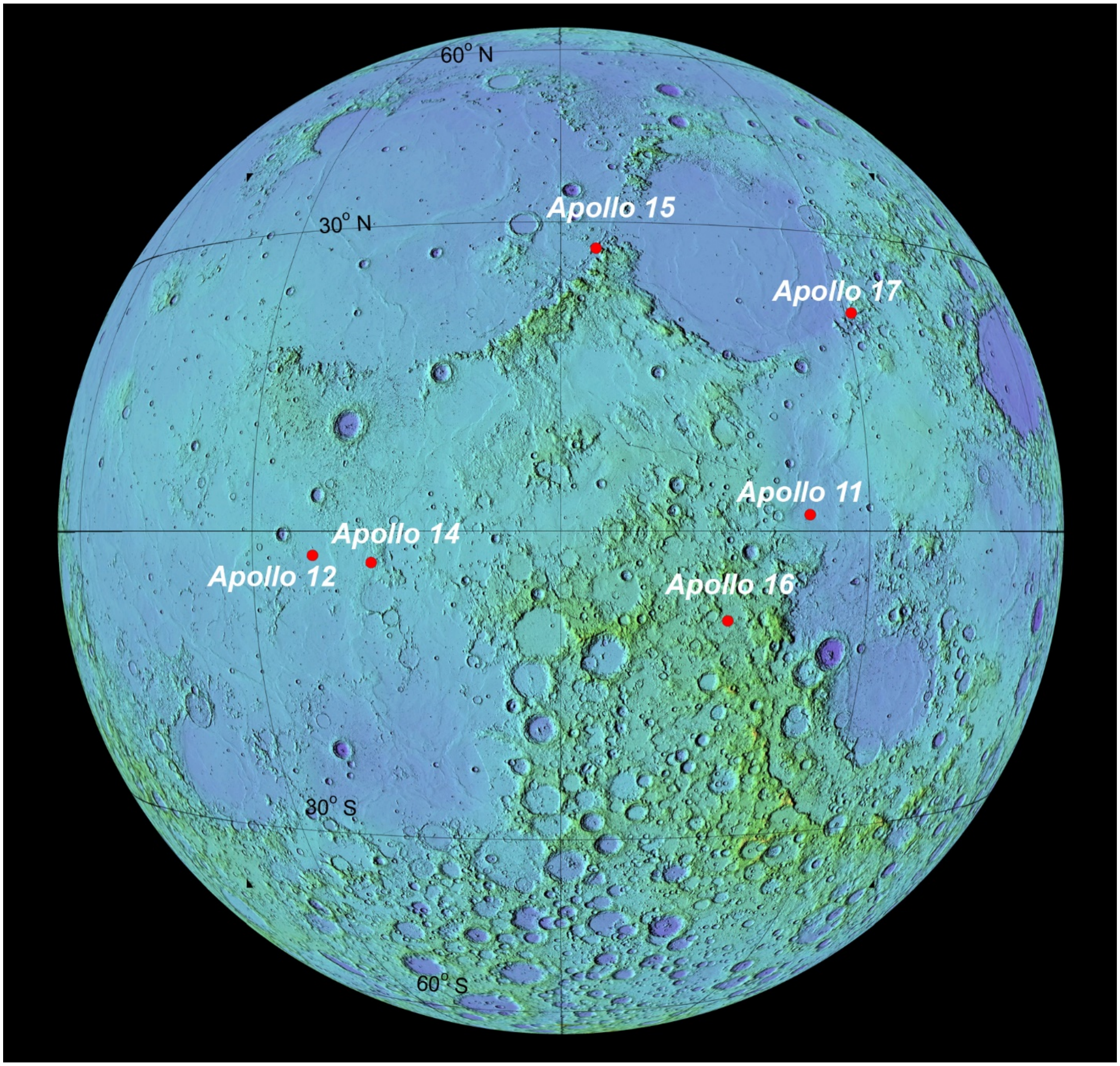

Fig. 1. A map of the lunar surface topography generated with the geographic information system using the database of the United States Geological Survey (Hare et al, 2014) showing Apollo landing sites.

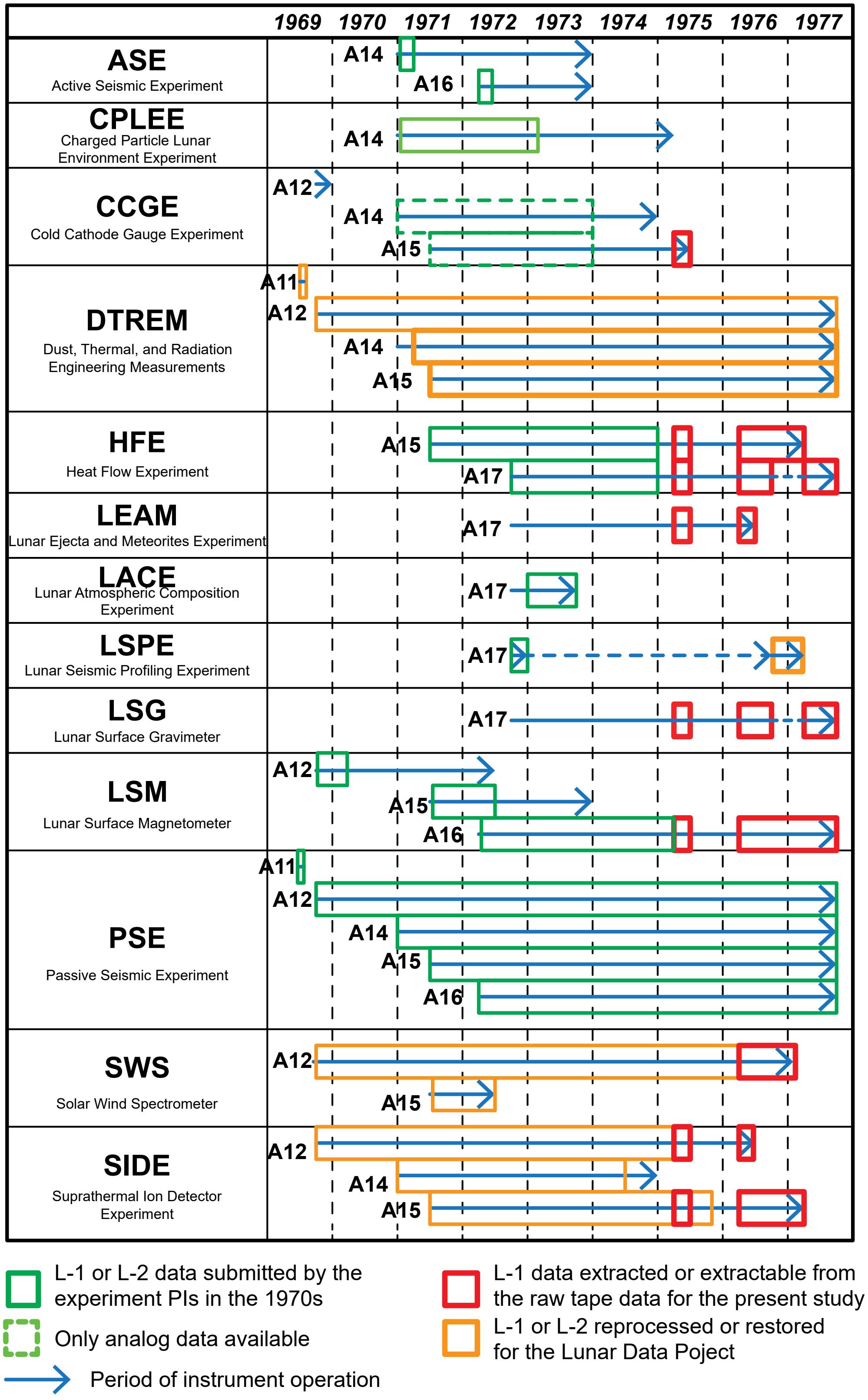

Figure 2. Operation timelines for the individual ALSEP experiments and data availability.

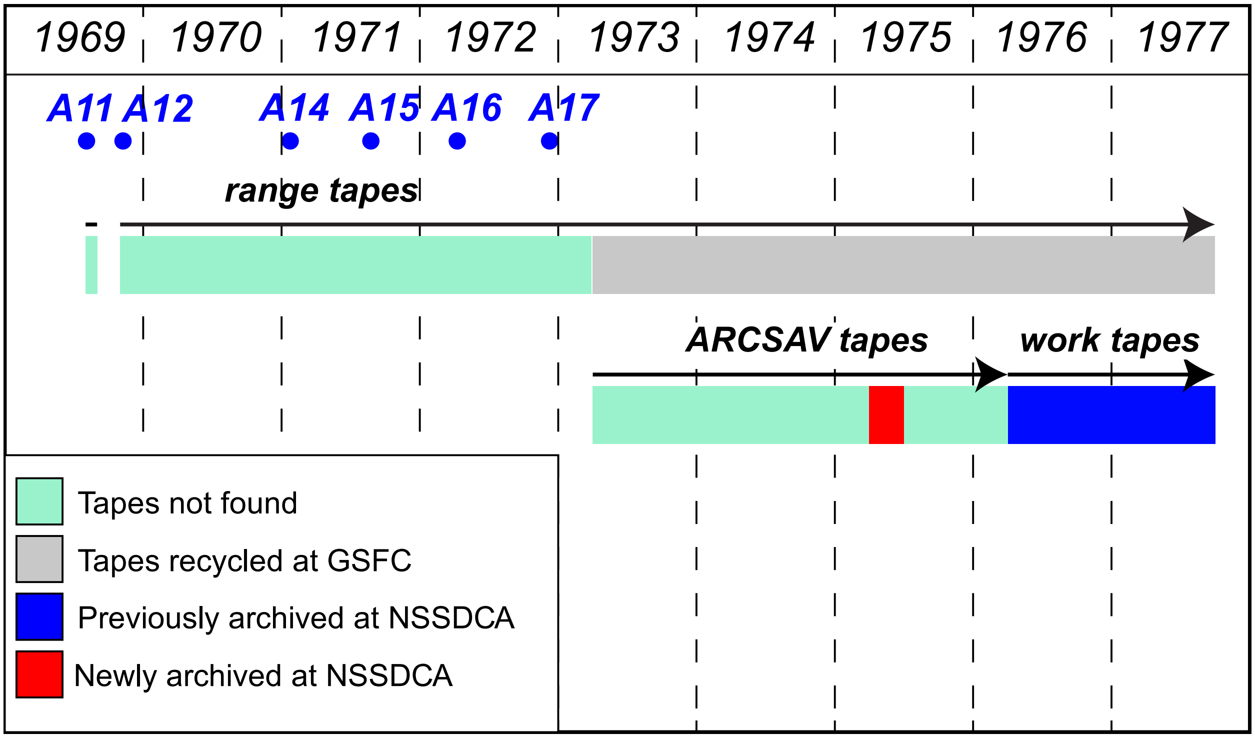

Figure 3. Production timeline for the ALSEP raw data (Level-0) archival tapes, and the status of the data extracted from these tapes.