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The process of bringing dark data to light: The rescue of the early Nimbus satellite data

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ABSTRACT

Myriad environmental satellite missions are currently orbiting the earth. The comprehensive monitoring by these sensors provide scientists, policymakers, and the public critical information on the earth's weather and climate system. The state of the art technology of our satellite monitoring system is the legacy of the first environment satellites, the Nimbus systems launched by NASA in the mid-1960s. Such early data can extend our climate record and provide important context in longer-term climate changes. However, the data was stowed away and, over the years, largely forgotten. It was nearly lost before its value was recognized and attempts to recover the data were undertaken. This paper covers what it took the authors to recover, navigate and reprocess the data into modern formats so that it could be used as a part of the satellite climate record. The procedures to recover the Nimbus data, from both film and tape, could be used by other data rescue projects, however the algorithms presented will tend to be Nimbus specific. Data rescue projects are often both difficult and time consuming but the data they bring back to the science community makes these efforts worthwhile.

1. Introduction

A myriad of environmental satellites are currently orbiting the earth. The continuous monitoring by these sensors provides scientists, policymakers, and the public critical information on the earth's weather and climate system. While technology of our satellite systems have greatly improved the quality of observations, it is the legacy of the first global coverage environment satellites, the Nimbus systems launched by NASA in the mid-1960s, that marks the beginning of a unique perspective from space. Such early data can extend our climate record and provide important context in longer-term climate changes. Unfortunately, the Nimbus data was largely forgotten over the years. It was nearly lost before its value was recognized and attempts to recover the data were undertaken. While the Nimbus data was never truly lost, it was in a form that could not be read and was not organized in a way that could be accessed with modern computer systems. The rescue and recovery of the Nimbus data began in 2007 with an initiative by the NASA Goddard Space Flight Center. Without the Goddard efforts, the early Nimbus data might be forever dark. This paper covers what it took the authors to recover, navigate and reprocess the data into modern formats so that it could be used as a part of the satellite climate record. The procedures to recover the Nimbus data, from both film and tape, could be used by other data rescue projects, however the algorithms presented will tend to be Nimbus specific. Data rescue projects are often both difficult and time consuming but the data they bring back to the science community makes these efforts worthwhile.

1.1. Nimbus in historical context

Over 50 years ago, in the early 1960s, NASA began development and launching a series of experimental weather and climate monitoring spacecraft in coordination with the U.S. Air Force. The primary sensors were visible light and infrared instruments (NASA's first passive microwave instrument flew on Nimbus V in 1973). In the early days of the 1960s Nimbus Program, the focus was almost entirely on meteorology. The Nimbus I, II, and III satellites carried High Resolution Infrared Radiometers (HRIR) as well as the Medium Resolution Infrared Radiometers (MRIR). Nimbus IV had the more advanced Temperature-Humidity Infrared Radiometer (THIR). All instruments were designed and implemented to record twice-daily global meteorological observations. The first two satellites also carried an Advanced Vidicon Camera

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System (AVCS), an analog system with the equivalent of 4-bit imagery. Nimbus III and IV carried the Image Dissector Camera System (IDCS), which had similar gray scale bit depth, but a much wider swath. The analog transmitted imagery was temporally recorded on tape and then played back and displayed on a video monitor. The images were permanently recorded by taking still photos of the playback display monitor. The early satellites also carried a low resolution Automatic Picture Transmission (APT) system for near real time data transmission [1].

Nimbus I launched on August 28, 1964, however the Agena upper stage failed and left the spacecraft in a usable elliptical orbit. The spacecraft failed on September 22nd 1964 when the solar panels became locked. Although the Nimbus I spacecraft only operated for a few weeks, the instruments were operational during the 1964 Arctic sea ice minimum, and the Antarctic sea ice maximum. This is the only known observation of the total extent of the ice pack in that year. The other early Nimbus satellites serendipitously also captured the Arctic sea ice minimum, and the Antarctic sea ice maximum during their times of data collection. Nimbus II was launched on May 15, 1966 and some of the instruments operated until November 15th 1966 when the tape recorder failed. The Nimbus III spacecraft was launched on April 14th 1969 and transmitted data from its instruments until January 25th 1970. Nimbus IV launched April 8th, 1970 and collected data until April 14, 1971, when problems with the spacecraft's ability to maintain Earth pointing began. In addition to the visible and infrared data, these early Nimbus satellites collected data from an increasing complex suite of instruments and are beyond the scope of this paper. The observational data was originally archived on a mixture of film and digital computer tapes. The archived second generation processed digital data has been recovered and is available online from the Goddard Earth Sciences Data and Information Services Center. Below is an image of Nimbus III undergoing testing at the Goddard Space Flight Center (see Fig. 1).

The early Nimbus instruments monitored Earth's meteorological, oceanographic and terrestrial data. Nimbus revolutionized weather forecasting and recorded the first large scale images of Europe and much of the earth from space. Nimbus II recorded the passage of Hurricane Betsy in 1966, the first hurricane to cause a billion dollars damage in the U.S. Nimbus III observed the 1969 path of hurricane Camille, one of the most destructive storms in U.S. history.

After initial analysis in through the 1970s [2,3] the Nimbus data was placed in long-term storage facilities until it was recognized that there might be useful climate data that could still be recovered nearly 50 years after the data was first acquired. This paper will focus on the project to recover the visible and infrared data produced by the first four successful Nimbus satellites (See Fig. 2).

2. HRIR data recovery process

2.1. HRIR sensor

The Nimbus High Resolution Imaging Radiometer (HRIR) instrument had a nadir resolution of approximately 8.5 km on the ground, which was high resolution in that time period. The HRIR detector operated in the 3.5–4.1 μ infrared band, where the influence of CO_2 and water vapor absorption was minimized. Since the sensor was fixed and used a scanning mirror to provide image swaths (a line perpendicular to the spacecraft motion), the resolution of the system decreased to about 35 km × 20 km at the edges of the scan [4]. The HRIR as well as the Medium Resolution Imaging Radiometer (MRIR), and the visible light Automatic Picture Transmission (APT) Camera were all mounted on the nadir face (bottom) of the spacecraft. It was a very early three axis stabilized system with a ±1° resolution pointing accuracy [5].

2.2. HRIR tape recovery

In 2007 NASA's Goddard Space Flight Center (GSFC) began a project to determine if digital data from old NASA satellite missions could be recovered. NASA knew that second generation Nimbus II data tapes containing HRIR data still existed in the National Archives in Washington, DC. According to manufacturers' data sheets and other technical literature, thirty years appears to be the upper limit for magnetic tape products [6]. Given that the Nimbus II tapes were already over 40 years old it seemed unlikely that any useful data could be recovered. The first step was to find and examine the tapes as time was running out. The Federal Record

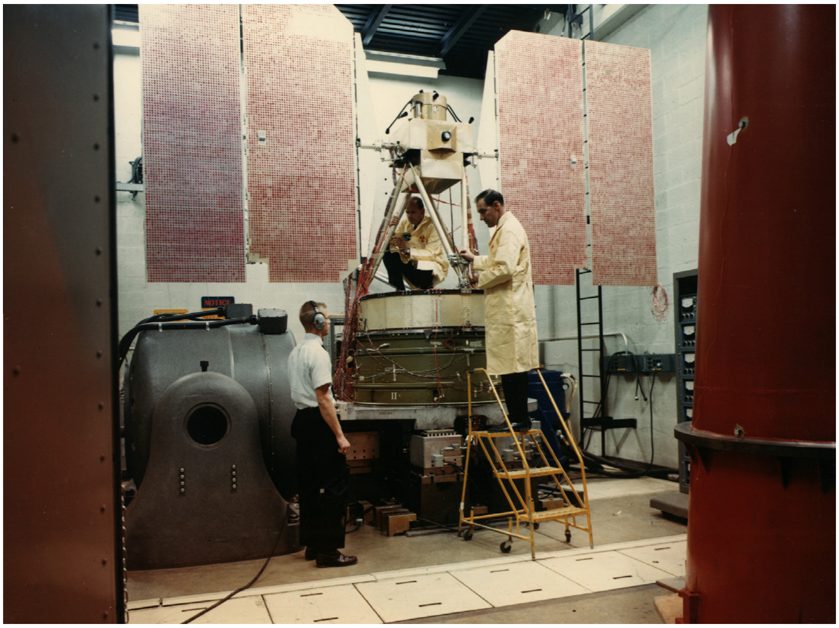
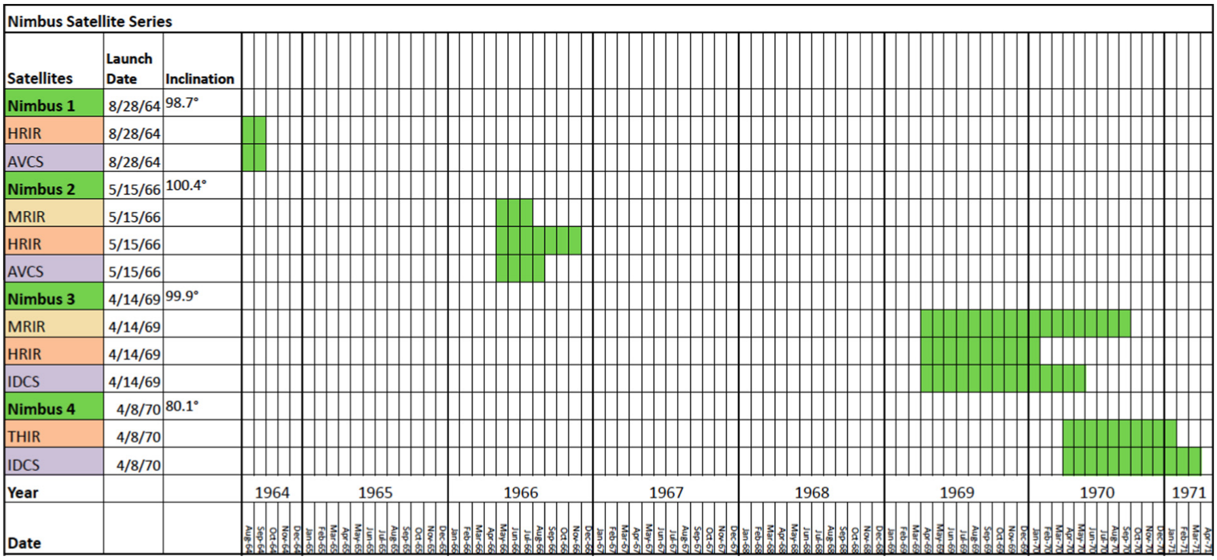


Fig. 1. Nimbus III on a shake table at the Goddard Space Flight Center 1967. Note the deployed solar cells.



Nimbus Satellite Series

Satellites	Launch Date	Inclination
Nimbus 1	8/28/64	98.7°
HRIR	8/28/64	
AVCS	8/28/64	
Nimbus 2	5/15/66	100.4°
MRIR	5/15/66	
HRIR	5/15/66	
AVCS	5/15/66	
Nimbus 3	4/14/69	99.9°
MRIR	4/14/69	
HRIR	4/14/69	
IDCS	4/14/69	
Nimbus 4	4/8/70	80.1°
THIR	4/8/70	
IDCS	4/8/70	

Fig. 2. Timeline of visible and infrared data from the early Nimbus I–IV satellites. Green squares indicate the sensor, month and year of operation from the NSSDC Master Catalog Search. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Center, which stored the HRIR tapes, contains vast temperature controlled storage rooms with aisle containing multitudes of tapes from many sources and agencies. The GSFC team spent days searching for the Nimbus tapes. This was made more difficult as the labels had often fallen off or become unreadable. Many of the boxes listed in the catalogs missing or misplaced [6]. An examination of these 7-track tapes revealed they were in poor shape. The tapes iron oxide media was falling off the acetate film backing. Fortunately, GSFC had just learned of a Canadian company, JBI Incorporated that had developed a tape recovery process that could read the bits from magnetic tapes with a high degree of certainty. The JBI recovery process involved using specially developed tape drives with 36 magnetoresistive (MR) heads, tape baking (10 h at 175°), bit detection and processing techniques to read the 800 bit-per-inch, 7-track tapes. Based on the original Nimbus HRIR system documentation, GSFC was then able to recover and rescue the observations from thousands of Nimbus HRIR digital data tapes [7]. The resultant Tape Archive Program (TAP) format data were sent to GSFC for digital storage. GSFC staff published the results at the 2008 American Geophysical Union Fall Meeting [8]. Researchers at the National Snow and Ice Data Center (NSIDC) noticed the HRIR instrument collected data over the poles. It was thought that it might be possible to use this data to determine sea ice extents in the 1960s [4].

2.3. HRIR data correction

GSFC initial examination of the recovered Nimbus HRIR files revealed what appeared to be a systemic scan line registration error or harmonic distortion (appears as a jitter in the image) that reduces their utility for ice studies. The records are variable length because the Spacecraft was in an elliptical orbit – and as its height increased and decreased the number of samples, sample size and scan width varied slightly. The original HRIR data was recorded as analog signal, which were received and stored on analog magnetic tape. These were digitized using an HRIR A/D signal processor and fed into a CDC 924 digital computer for preprocessing. These tapes were then were fed into an IBM 7094 computer for post processing. Only the later IBM 7094 GSFC post-processed tapes were archived. The data on these tapes had radiometric calibration applied and all supporting calibration and synchronization information was removed before the data was written to tape. The raw record can be visually seen in Fig. 3.

In Fig. 3 above, the line units are voltages that represent emission of radiation from the Earth at night (most HRIR observations were taken in the nighttime to avoid seeing sun reflection in the Near IR). As part of the original processing, calibration was applied and equivalent black body temperature values were derived for each sample. Each line is a swath and it represents a scan of the Earth perpendicular to the direction of travel of the satellite. Fig. 4 shows the nature of the problem with the HRIR data:

NSIDC was awarded a small grant funded by the Innovative Research Program (IRP) at the Cooperative Institute for Research in Environmental Studies (CIRES) to study the use of the Nimbus II HRIR data and to determine if it was possible to reconstruct sea-ice extents from the 1960s. The project had the initial goal of developing an approach for correcting the HRIR digital files recovered by GSFC. NSIDC knew of an ongoing effort by the Lunar Orbiter Image Recovery Project (LOIRP) [9] team at the NASA Ames Research Park that researched potential artifact corrections, based upon reprocessing of analog Lunar Orbiter images. The Lunar Orbiter project began in 1966 with the goal of helping to determine potential landing sites for the Apollo lunar landings. Many of the techniques needed to recover and process the Lunar Orbiter data were similar those needed for the Nimbus HRIR dataset. NSIDC contracted the LORIP team to determine if software could be developed to correct the error. NSIDC researched and searched for the original Nimbus II data in coordination with LOIRP. Study of the data revealed a repeating, semi-random horizontal shift in each swath. The cause could be related to problems detecting the Earth's horizon for digitizing the Earth view part of the analog recording. The removal of the synchronization pulses in the original post processing made identifying the cause ambiguous. Additional analysis further revealed very cold temperature samples at the left of many swaths whose pattern of introduction was so tightly correlated with the artifact as to suggest a means to improve the relative registration of each swath.

The "coldness" was due the fact that space (just to the right of the synchronization pulses in Fig. 3) was imaged right after the sync pulses. Since space is a 4 K background, the temperature was below the calibrated range of the HRIR sensor. Computer processing of the data in the 1960s set any temperature that was below the minimum calibrated temperature of the sensor (205 K)

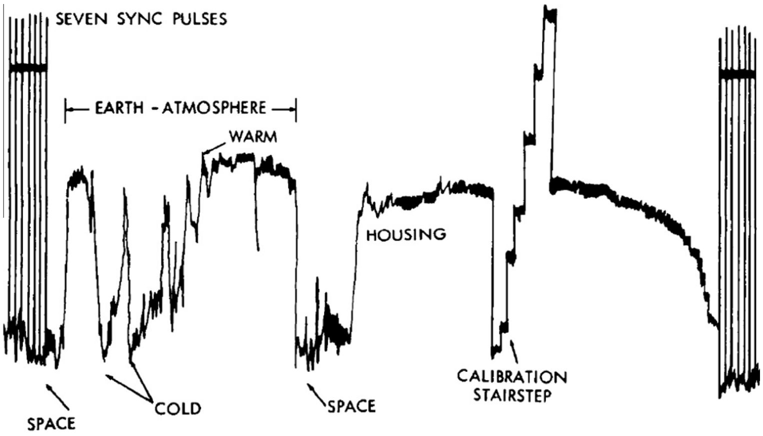


Fig. 3. Structure of a raw Nimbus Image Row showing synchronization pulses and calibration steps from the Nimbus II Users Guide.

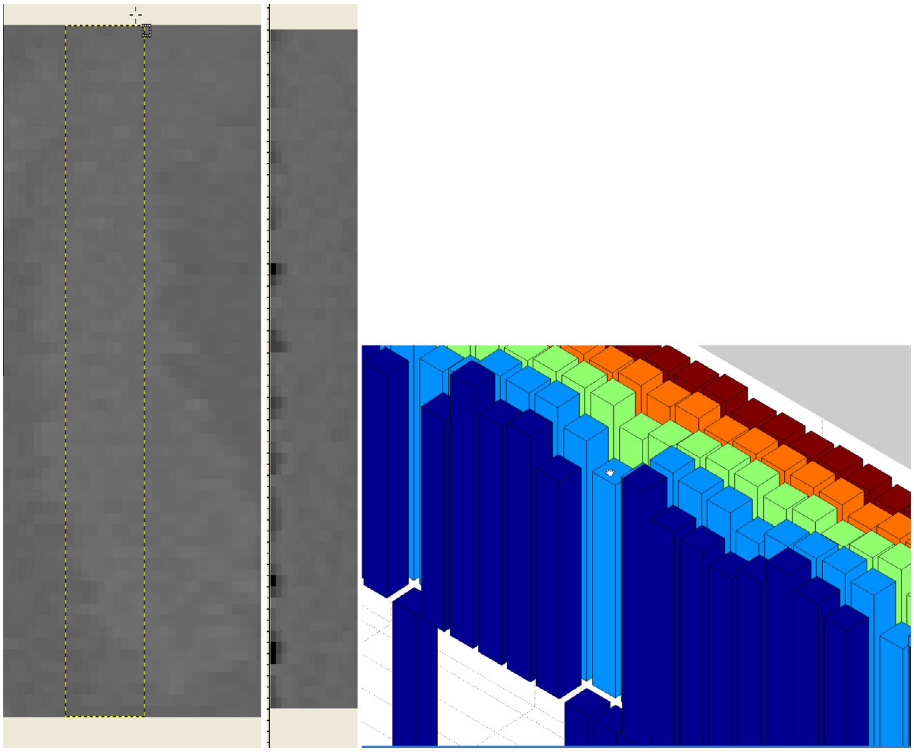


Fig. 4. Close up of Lake Michigan and periodic error in scan line registration in Nimbus II recovered data. The periodic errors have distorted the shape of Lake Michigan (leftmost image) are the result of a shift in the lines of temperature data in the swaths [4].

to 190 K so that future researchers would know that the data was invalid. Further analysis of the image reveals that periodic offset in the scan line registration of the original analog recording caused a repeatable shift in the data (Fig. 5 left image). The analysis suggests (right hand image) a means to derive offsets that may be applied to all recovered images. The basic correction method was tested by manually shifting ~60 swaths overlapping with Lake Michigan. Each swath was shifted left until any extremely cold temperature samples at the left were no longer visible. The magnitude of shift, ranged between 0.0 and 3.5 pixels (w/1 HRIR measurement sample exactly equal to 1 pixel). However, with 2470 TAP files to process, and approximately 1100 swaths per TAP file, there are over 2.7 million swaths to correct, rendering the general application of a manual solution impractical.

Based on the above analysis, NASA funded NSIDC to develop a Nimbus HRIR scan line registration, geo-location and gridding software. The end result was to be a monthly estimate of Arctic and Antarctic sea ice extents from the available data. The LORIP team developed software to convert the original Nimbus 2 HRIR TAP format files into the intermediate file format. As a part of this effort they developed ray trace algorithms and associated software for mapping each pixel in the original orbit swath to a latitude-longitude position. These algorithms used the actual Nimbus II HRIR orbit and instrument scanner characteristics to derive pixel geo-location.

When the original analog data was truncated, both the calibration and synchronization pulses were removed. This meant that the method developed by the LOIRP team for the Lunar Orbiter images, was not fully applicable. The LORIP and NSIDC team then developed a new correction for the periodic error that is traceable for future researchers to maintain the scientific integrity of the data [10]. The HRIR records have 31 anchor points, which are

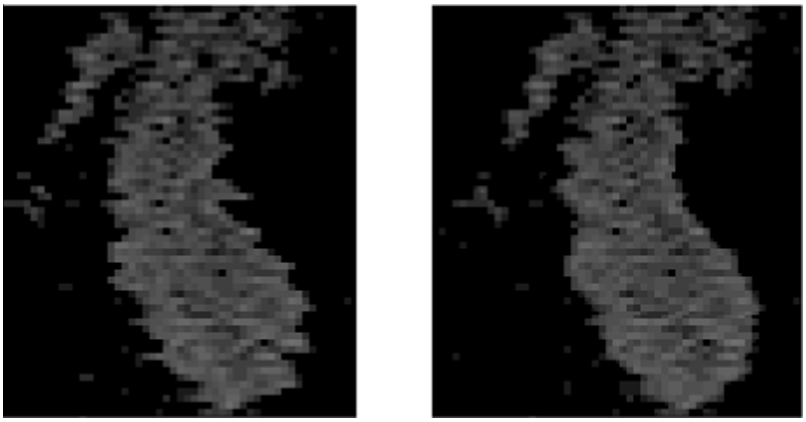


Fig. 5. Original and registration-corrected HRIR images of Lake Michigan from 1966. One the left image, note the "tearing" of Lake Michigan at the pixel (swath) level. The quality of the result on the right image reveals that the correction solution found is highly viable [4].

longitude/latitude pairs that describe a function of where to place the digitized temperature data on the Earth. These points were originally intended for use to register prepared latitude–longitude grids for overlaying on the image. An attempt was made to use this metadata to translate the swaths to the Google earth KML format. When these anchor points were used with various interpolation schemes, the resulting mapping of the image to Google Earth was a complete failure. After many attempts to use the anchor points in some manner that would work, the effort was abandoned for the approach below.

The latitude and longitude for every pixel was listed on the raw data tapes. But the scan lines need realignment due to the random error (±3.5 pixels) in detecting the start scan pulse. The basic idea for realignment was to compare individual scan lines with a running average. The first step in the iteration was to construct running mean arrays of the data. Next, each raw scan line was compared to the smoothed scan line, shifting left right to maximize the correlation. The best shift removed the misalignment error. This worked well in situations with sharp gradients in the images (for instance cold clouds). This process was repeated 3 times to align the data. In areas with very small gradients, the correlations did not lock onto any feature, however, if the temperature of a large area is constant, it does not make any difference if the scan lines have a misalignment. This final scheme was developed as collaboration NSIDC and LORIP.

The geometric computer codes (from all three outputs) were checked by comparison with landmarks and geography on the Earth. There were still residual navigation errors because the satellites did not have perfect control of roll, pitch and yaw. For some frames used in the derivation of the sea ice extent in the Arctic or Antarctic, linear shifts were applied to the images to force a match between the estimated location and the known landmark (This is documented in the sea ice edge data set). The corrected data was then converted to a scale-appropriate Equal-Area Scalable Earth Grid (EASE-grid) projection data file for each orbit. Finally netCDF compatible files were developed from the EASE grid data file of each orbit for all the Nimbus II HRIR orbit files into netCDF CF-1 files. NSIDC then processed the Nimbus I, II, III and IV data using this software and algorithms.

The metadata incorporated into each swath had three features that enabled the data to be mapped on Google Earth. The first and most important is the sub-satellite point, which is the intersection of the spacecraft's nadir face to the Earth. The second was the beginning and ending latitude/longitude from the anchor points and the altitude of the spacecraft for each data record, which was provided every six swaths. This information, along with the field of view of the sensor, was used to ray trace the corners of each individual temperature record to the spherical shape of the Earth at the altitude of the spacecraft. Colors were then assigned to the temperature records from the metadata. Fig. 6 is a full day of Nimbus II image swaths mapped to Google Earth:

The Nimbus HRIR data could be used to estimate 1960s sea surface temperatures, locate positions of major oceanic and lake currents as well as provide insight into hurricanes of those times. Unfortunately, the HRIR data were not ideal for determining the sea ice extent due to the variability and inconsistency in sea ice and ocean surface temperatures, it was difficult to distinguish the ice edges as the temperature of the ocean and the ice could be nearly identical. In an effort to find the sea ice extent, the project shifted to the Nimbus AVCS and IDCS visible light film data. However, experimental work undertaken by the LORIP team indicated very good correlation to tracking data for 1966 Typhoons. Typhoon Ida is visible near the top of the KML overlay on Google earth.

3. AVCS/IDCS data recovery process

3.1. AVCS/IDCS sensors

The AVCS used video technology to collect images of the reflected radiance from the Earth every 91 s. The Nimbus I and II AVCS sensors consisted of three vidicon cameras to produce a three-image composite. Each camera covered a 35-degree field of view with the center camera pointing at nadir. The 800-scan-line, 2.54-cm vidicon tubes had a resolution of 1 km at nadir at an altitude of 1100 km. Detailed instrument description can be found in the Nimbus II User Guides [5]. Navigation of the images is based upon the orbit elements, time of measurement and geometry of the AVCS cameras. Notice that latitude/longitude marks were included in the archive imagery. The calculated lat/lon values generally disagree with this information burned into the images because the after the fact orbit elements were better than the predictions used in the 1960s real time navigation. Although most images have a gray wedge, which was designed for calibration, variations in the camera sensitivity on the satellite and digital to analog data capture processes made it difficult to construct a "calibrated" radiance from the data. The data are, at best, 4-bit resolution so fine details of clouds are not evident (Fig. 7). The coverage with Nimbus II in 1966 was better because the higher observational altitude (1100 km) and 20% overlap between images, however the data are noisier. The authors suspect this was due to a failing video monitor.

The Nimbus Image Dissector Camera System (IDCS) was a shutterless electronic scan and step tube camera system with a

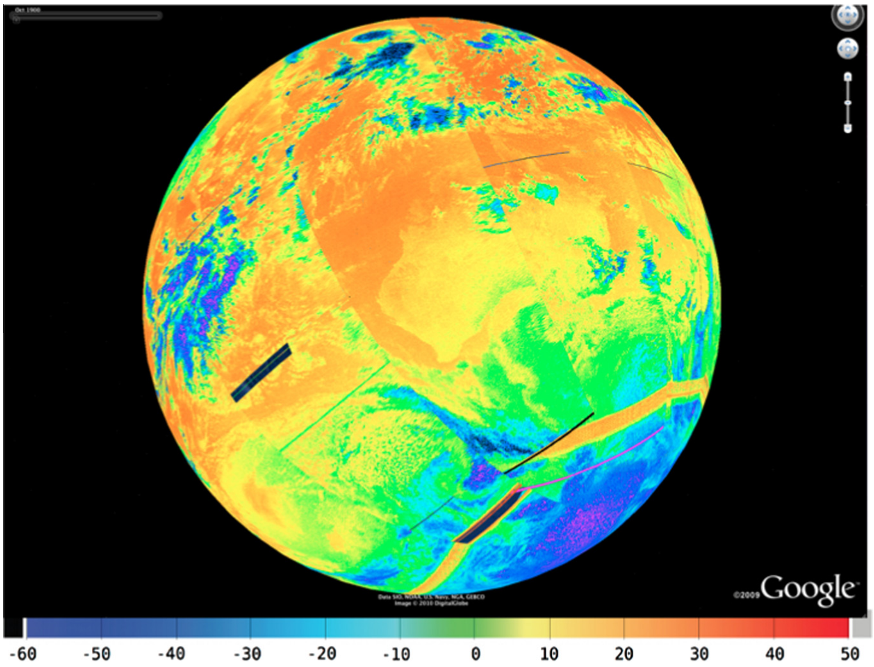


Fig. 6. Google Earth Mosaic of Nimbus II False Color Temperature in degrees Celsius from September 23, 1966. Note the Indian Monsoons (left), Pacific typhoons (top) and Cold Temperatures in Antarctica [4].

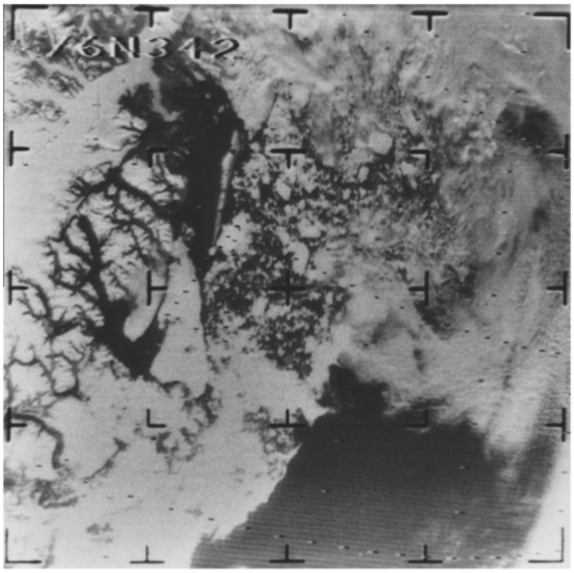


Fig. 7. Nimbus I, AVCS, Eastern Greenland, near Daneborg September 2, 1964. Note the ice pack in the center of the image.

108-degree wide-angle lens (Fig. 8). The field of view was 73.6° along track, and 98.2° across track. The pictures could be stored on magnetic tape for later playback or transmitted to APT (automatic picture transmission) stations. The Nimbus III and IV IDCS images at an altitude of 1100 km cover a wider extent and the images have significantly better dynamic range and overlap than the older AVCS images, however the resolution is lower.

The analog signal from the AVCS and IDCS camera data were recorded on analog tape on the satellite and then transmitted to the Alaska ground station or on to the Goddard Space Flight Center with in 100 min of the observations. The signal was displayed on a slow scan TV and photographed with a black and white film camera, AVCS at 35 mm and IDCS at 70 mm. That film was then archived as the only long-term storage of the observations.

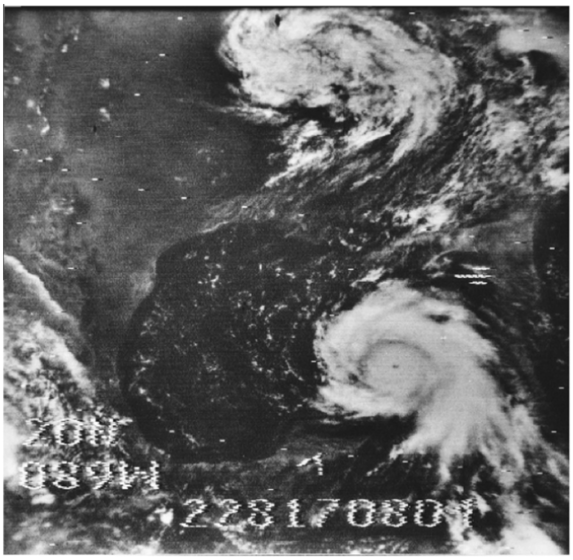


Fig. 8. Nimbus III IDCS image of Hurricane Camille August 16th 1969, one of the most powerful storms to ever hit the United States.

3.2. AVCS/IDCS film recovery

The AVCS and IDCS film was stored in Suitland, Maryland after the primary analysis was completed. After 25 years in an uncontrolled environment the film was moved to the National Climate Data Center (NCDC) in Ashville, NC. From 1987 until this project the film canister sat unopened at NCDC. This was not due to a lack of interest in the data but rather the inherent difficulty in extracting any desired data. The 50 boxes each contained 4 or 5 canisters of 200-foot reels of film. The images were located randomly on the film with images separated by between 2 in. to as much as 3 feet. There were 112 35 mm AVCS rolls and seventy 70 mm IDCS film rolls for Nimbus I, II and III. Each 200-foot 35 mm film roll is estimated to contain 1250 images, while the 200-foot 70 mm film rolls are estimated to contain 750 images. The only information on the canister was the date range and the orbit numbers (Fig. 9). Therefore the only metadata available for the Nimbus film was the date. Over the 25 the years that the data had been stored at NCDC, they had not had a single request for delivery of any Nimbus data. Our project really needed only the polar-regions; however, there was no possible means of getting to that data unless we requested all 50 boxes and scanned them all.

Our early efforts to digitize the Nimbus film data were started under the NOAA Climate Data Modernization Project (CDMP) with an accepted proposal. The CDMP blazed a trail in data rescue efforts especially in the recovery of film records. Unfortunately, the CDMP program was canceled however we were able use many of the techniques described below, that were first initiated by the CDMP and their contractors.

In 2010 the Nimbus AVCS and IDCS rescue project began in earnest with our remaining NASA funds. This was no small undertaking as the film took up 2 pallets. In addition, long roll film scanners were becoming scarce as film media was passing into technological obsolescence. The project required a scanner that could consistently and reliably scan both 35 mm and 70 mm film at high resolution. The solution was a second-hand 2004 vintage Kodak HR-500 long roll scanner, purchased for about $40,000. University of Colorado students provided the labor pool for scanning and metadata development.

There were a grand total of about 250,000 images from all 4 Nimbus missions. Several major hurdles had to be overcome to successfully scan all of these images. First, there was no automated way to detect the image frames on the film. The scanner software was designed for images that were consistently positioned on the film and Nimbus images were randomly placed on the film. This meant we would have to scan every inch of film on the reel. Additionally it meant that the images were usually split, as the scanner could not detect the start of an image frame. To solve this, post-processing software was developed by the project to splice the split images back to whole frames. As a result, the scanner had to scan millions of frames to capture the quarter million images. The metadata consisted of the date, hour, minute, and second of the exposure as well as the location of the center of the image. A significant setback to the project was the discovery of automated image brightness stretching by the scanner. This unwanted stretching feature automatically rebalanced the exposure of each frame and created images that were not true to the original data. This scanner default setting was locked on in the software. Thousands of images had to be rescanned as a result.

Asking the students to manually key input the 250,000 time stamps, center locations and delete all the missing scans was not going to produce a quality work product. There was a real concerned about the mental health of the students doing the work. A software program was developed using a game like interface to keep the students engaged while automating as much of the work as possible. The satellite captured an image every 91 s and the image times were displayed at the bottom of each image, however 60% of the time the data was illegible. The software resolved this by trimming off and displaying this text at the bottom of the screen (Fig. 10).

With these procedures developed, the student had to select only one time stamp per half orbit that they could read and the system would calculate the rest of the information automatically. The next step was to tag the image center fiduciary mark. The system would then use the timestamp to calculate an image location based on North American Air Defense Command (NORAD) ephemeris data from the Nimbus data. NORAD still has the orbital data of every mission ever launched. This information resulted in a plot that indicated the image location relative to continental outlines (Fig. 11).

This software resulted in a greatly improved metadata creation process [11]. Over 100 frames of metadata can be created in under 10 min. The students could simultaneously scan the images while creating the metadata. NASA then funded the scanning of Nimbus IV. These techniques were used on all the film reels from Nimbus I, II, III and IV. With this data it became possible to construct some of the 1960s sea ice extents.

3.3. AVCS and IDCS navigation algorithms

The original 1960s AVCS navigation was in the form of latitude longitude map ticks burned into the film images but this was found to be in accurate and not recoverable from the film. The image time stamp (recorded on the film) together with the two-line element orbit information was used to reconstruct the satellite position at the time of the observation. The Advanced Vidicon Camera System geometry was reconstructed to estimate the location of each pixel in the image relative to the center fiducial mark. The student scanners recorded the center pixel and the time for the more than 100,000 images scanned. The center location of camera

Fig. 9. Nimbus AVCS 35 mm film canisters from the National Climate Data Center in Ashville SC.

Fig. 10. Trimmed portion of base of AVCS images and calculated corresponding time stamp in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

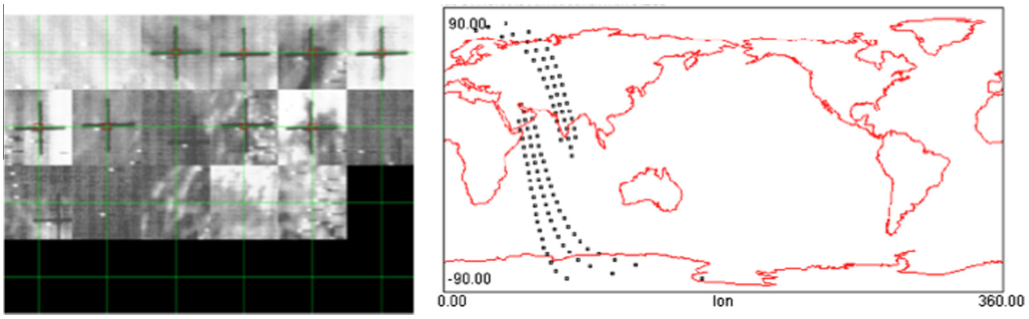


Fig. 11. Tagged image center points and resulting image location navigation based on NORAD orbital data.

2 was assumed to view the orbit track just below the satellite. The geometry of each of the three cameras was developed based upon the Nimbus I and II user guide instrument schematics (Fig. 11). Interestingly the relative angles between the three cameras were the same angles as used in World War II reconnaissance aircraft. Basically, imagine a pinhole camera viewing a sphere (the Earth). The camera looks straight down (camera 2) or left or right at 35 degrees (camera 1 or 3) (Fig. 12).

In more detail, the AVCS navigation software is based upon the following geometry:

First we know the location of the spacecraft is known from the orbit elements and the time (from NORAD ephemeris data). That is represented by the vector $\vec{\boldsymbol{V}}_{\mathbf{s}}$. The unit vector normal to the orbit plane is $\vec{\boldsymbol{U}}_{\mathbf{n}}$. The vectors for the camera centers will then be:

$$\vec{\boldsymbol{r}}_{\mathbf{e}} = \vec{\boldsymbol{V}}_{\mathbf{c}} = \vec{\boldsymbol{V}}_{\mathbf{s}} + d^{*}\cos(c)\vec{\boldsymbol{U}}_{\mathbf{n}}. \quad \text{where } c = -35^\circ, 0^\circ, 35^\circ$$

Solving for d can be accomplished by setting the length of $\boldsymbol{V}_{\mathbf{c}}$ to the distance from the center of the earth to the surface in the latitude/longitude region of the viewed point. This requires some iteration because the earth is not a sphere. A solution just involves the law of cosines for a triangle. Next consider a raster image from each camera. These points are relative to the vector at the camera center. Define the cross track, $\boldsymbol{C}_{\mathbf{1,2,3}}$ and along track, $\boldsymbol{A}_{\mathbf{1,2,3}}$ unit vectors normal to the center vector ($\boldsymbol{V}_{\mathbf{c}} - \boldsymbol{V}_{\mathbf{s}}$).

The observed points are then:

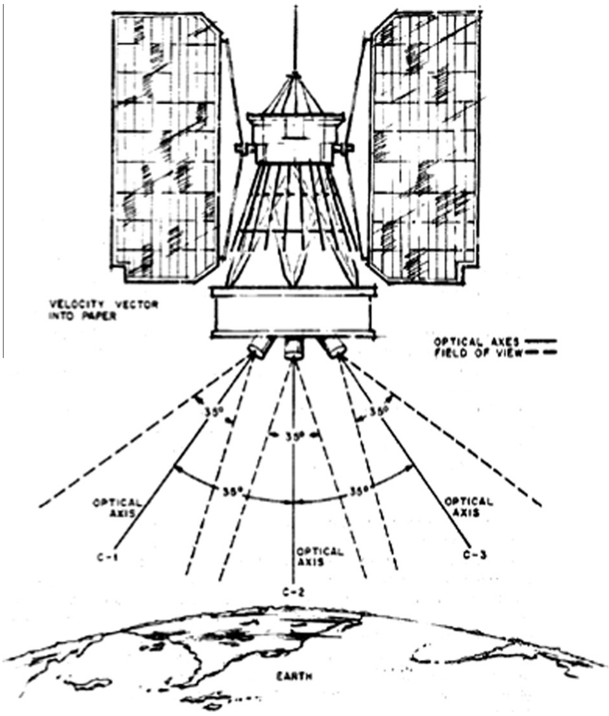


Fig. 12. Orientation of the three AVCS cameras at the base of the Nimbus satellites, from the Nimbus II User Guide.

$$\vec{r}_0 = \vec{V}_c + \left(\sin(\Theta)^* \vec{C}_{1,2,3} + \sin(\Phi)^* \vec{A}_{1,2,3}\right)^* d'$$

$$\Theta = (i - ic)^* D_a$$

$$\Phi = (j - jc)^* D_a$$

where i and j are the raster indices and D_a and D_a are derived empirically from the film size and the digitizing rate of the film scanner. Again from the law of cosines one can derive d by requiring the magnitude of $\vec{r}_0$ to be the radius of the earth. The latitude and longitude of each point is then determined from the vector $\vec{r}_0$.

Navigation of the Image Dissection Camera System data was complicated because of the need to simulate the motion of the spacecraft as the scan head scanned backwards along the orbit track for 202 s [12]. The scan across track was engineered with an electric drift tube on the spacecraft with no cross track mechanical motion. After the image was completed (202 s) the drift tube was rapidly returned to the start position (10 s) to initiate a new image (Fig. 13). The sequence of images had a 50% overlap with the previous image.

Proceeding upon the same plan as the AVCS navigation, the satellite location vector, $\boldsymbol{V}_s$, was determined from the orbit elements and the time of the image. Define a vector normal to the orbit $\boldsymbol{U}_n$ plane then a cross track vector normal those two: $\vec{U}_c$. As the drift tube detector rotates, it will point at the earth at a point

$$\vec{r}_c = \vec{V}_s + d^* \sin(a_{time})^* \vec{U}_c.$$

where a_{time} ranges from 34.4° to −35.3° over the 202 s of the picture scan. As the spacecraft progresses, the scan backtracks.

Again the satellite images are raster images where the successive scan lines correspond to changes in a_{time}. The cross track scanning is assumed to occur instantaneously from the drift tube electronic scan. Notice that $\vec{U}_c$ and $\vec{V}_s$ change with time as with each successive scan line.

$$\vec{r}_c = \vec{V}_s + d * (\sin(\Theta) * \vec{U}_n + \sin(a_{time}) * \vec{U}_c)$$

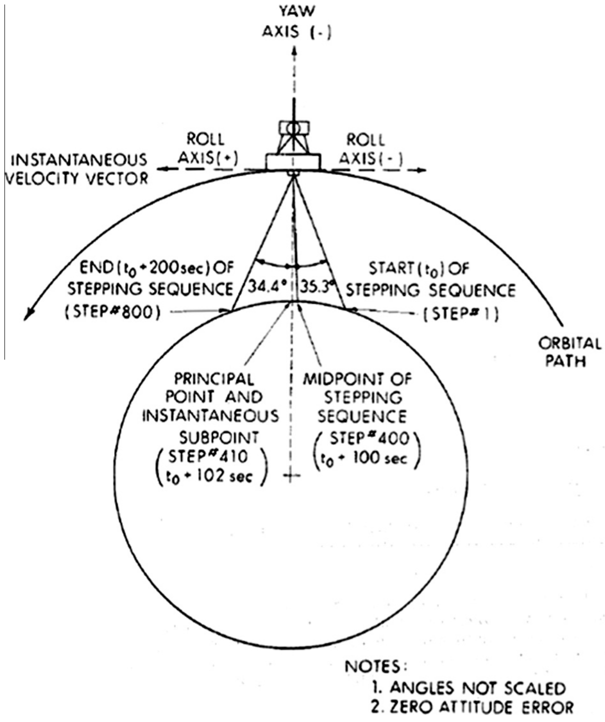


Fig. 13. IDCS scan head and timings relative to earth surface, from the Nimbus III User Guide.

Solving for the unknown distance, d, is accomplished by setting the length of $\boldsymbol{r}_c$ to the distance from the center of the earth to the viewed region. The rotation of the earth needs to be accounted for as time progresses for the IDCS camera.

All of this effort leads to a latitude, longitude at the earth's surface corresponding to every pixel in each raster image stored in the archive.

3.4. Building the sea ice extent

Gallaher, Campbell and Meier have described the techniques used to develop check and determine error estimates in detail [11]. Basically, all the polar images were viewed and the visible ice edges were manually digitized. This data was then divided into 2° longitude bins and averaged over the observed ice extents for each bin. About 4000 images were reviewed from Nimbus II to develop the four months of ice extents. After the average extent for each month was determined it was compared to an automated ice detection method. The automated ice detection methodology consisted of remapping and compositing the minimum brightness for all the polar images over a 5-day period resulted in a "cloud free" clear sky radiance (Fig. 14). Cloud-free ocean regions in single images appear dark. The clouds tend to move faster than the ice, so images that were white and stayed white over the 5 days are likely to be ice. This gives a qualitative impression of the location of the ice edge and provides an independent validation of the ice extent, however the variations in the calibration made it useful only as a check of the manual estimate. Visually, it shows a solid match between the average manual ice edge and the composite image picture.

4. Sea Ice Extent values results

The authors have provided 1964 Arctic sea ice extents in [13] and 1960s Antarctic sea ice estimates in [14]. The analysis of the Nimbus I, II and III missions for the Arctic sea ice extent data are consistent with the 1979 start of the modern satellite record, and lend more context for the strong downward trend since 1979.

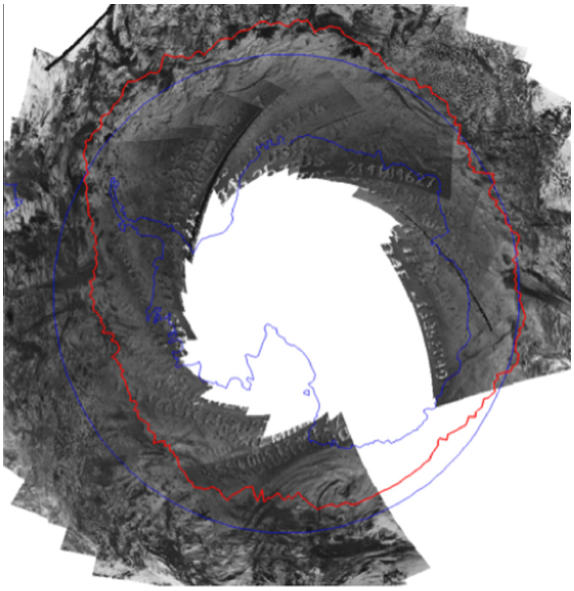


Fig. 14. 5-day Minimum IDCS brightness August 1–5, 1966. Superimposed in red is the sea ice monthly average edge from the manual analysis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The Nimbus records suggest that Antarctic sea ice extents in the 1960s varied significantly (both greater and smaller) than most of the modern 1979–2014 passive microwave record. The high sea ice variation in the Antarctic in the 1960s may represent more normal sea ice conditions. The Ozone Hole over the Antarctic may have been a factor with the ice extent over the last 30 years. Unfortunately, there is not a way to independently validate these estimates with other direct measurements of sea ice. However, proxy records can provide indications of sea ice conditions.

Methanesulphonic acid (MSA) derived from ice cores appears to function as an Antarctic sea ice extent proxy. Studies of the Law Dome Antarctica MSA record (from 1841 to 1995) and maximum sea ice extent in the 80°E to 140°E sector [15] appear to agree fairly well with the variation seen in the Nimbus Antarctic ice extents. The August 1966 and 1969 maximum observed sea ice extent may vary from the maximum MSA record as it was slightly earlier in the season.

5. Nimbus data archive

All of the visible images have been converted to HDF5 files, the standard NASA archive format for raster data. Every pixel brightness count has an associated latitude-longitude and quality flag. Similarly each orbit halves from the HRIR instruments are recorded as HDF5 files with the temperature tagged with lat/lon and quality. The Nimbus I, II and III data are in the searchable NASA archive system so one can ask for a location and time window and get back all the data overlapping that request. As of February 1, 2015 we are processing and uploading the Nimbus IV IDCS visible data.

The Nimbus IV THIR data is a bit more complicated because it has the same small misalignment between scan lines which can be corrected with software use for Nimbus I, II and III. But we must be sure that the lines are matching between channels because that is the power of multispectral imagery comparing the channels. That will be done by mid 2015 with insertion into the archive shortly after. The digital Nimbus HRIR data represents the oldest digital satellite data in NASA's data holdings.

All these data are now stored in modern formats and are available for general use via Goddard Earth Sciences Data and Information Services Center, http://disc.sci.gsfc.nasa.gov/nimbus and at National Snow and Ice Data Center, http://nsidc.org/data/nimbus/order-data.html.

6. Conclusions

To improve our understanding of the polar climates we have used the data to study the sea ice variations in the 1960's. This data has many other potential uses such as snow cover, lake levels and the impact of clear cutting forest. The Nimbus data is ripe for studies of tropical and mid-latitude weather and cloud variations, as this data exists long before any other satellite observations. Improved understanding of the hurricane and typhoon season is also provided by the Nimbus images, both AVCS and HRIR.

While this earlier sea ice record will not be as high-quality, complete, or consistent as the modern passive microwave record, there are several other sources of imagery that can be analyzed to provide valuable information before the multichannel passive microwave era began, allowing us to extend the sea ice extent record back to the mid-1960s to match the extended snow extent record that begins in 1967. In doing so, we will provide integrated fields of snow and sea ice cover extending back at least 50 years. The Nimbus missions cover only a small portion of the 1960s sea ice history. The ESSA 1, 3, 5, 7 and 9 missions cover much of the mid to late 1960s. These were satellites from Environmental Science Services Administration the precursor to NOAA's National Environmental Satellite, Data, and Information Service (NESDIS). Like Nimbus, they flew the AVCS cameras and offer an also continuous global satellite record from 1965 to 1970. Unfortunately, like Nimbus, this data is only available on long film reels. The ESSA and Nimbus data in combination with later visible, infrared and passive microwave satellite data would enable better characterization of long-term natural variability and assessment of future changes. However, accessing the historical satellite record is difficult as many of the original data sets have been lost. The time to recover this information is running out as the data, hardware and expertise are rapidly becoming obsolete. If this work is not done now, we may have forever lost the opportunity.

Considering the current state of data rescue efforts, we find that too often the data is being disposed of, as organizations believe the data is of poor quality or that the task is impossible. These records are often unique and there is no other source of observations that cover those periods. With rescued data, the problem must be adjusted to fit the data rather than adjusting the data collection to fit the problem. This usually requires rethinking the problem. Whatever state the data are in, they are vastly better than the data voids of our current situation. The techniques of bringing dark data back into the light, in modern formats, are critical to understanding long-term climate issues. The procedures used in the Nimbus data rescue projects are applicable to other historic data from other Earth-observing satellites as well as other historic digital tape and film records.

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