Robots in the Kingdom of Apollo

Lunar Orbiter Photography and the Scientist-Explorer in the Twentieth Century

by

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Biographical Sketch

The author is originally from Phoenix, Arizona. He attended Barrett, the Honors College at Arizona State University and graduated with Bachelor of Arts degrees in Philosophy and History in 2015. He taught World History at the secondary level and has written high school history and geography curriculum. He began his master's studies in history at University of Rochester in 2022. He was awarded a Dorothy Rosenberg-Passer Fellowship in 2023. He pursued his research in the history of exploration under the direction of Stewart Weaver.

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Abstract

In the twentieth century, scientists increasingly used remote sensing technologies to learn about distant places. This trend challenges some conventional ways of thinking about exploration as a historical process. This thesis focuses on the perspectives of the scientists and engineers who worked with the Lunar Orbiter spacecraft, to clarify the extent to which their activities departed from established practices of scientific exploration. NASA’s Lunar Orbiter program in 1966 and 1967 was tasked with finding sites for the Apollo program's crewed lunar landings. These efforts contributed to the emergence of a complex collaborative network between government officials, engineers, and scientists. The Eastman Kodak cameras onboard the Lunar Orbiter spacecraft enabled scientists to extend existing practices of scientific field work to the Moon. An analysis of Lunar Orbiter’s role in the Apollo program, discussions among scientists and their collaborators, and the scientific practices surrounding Lunar Orbiter photographs suggests ways in which this episode fits into a broader history of exploration.

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Introduction

On March 31st, 1927, George Hubert Wilkins climbed into a single-engine monoplane called the *Alaskan* with his pilot Carl Ben Eielson. They set out from Fairbanks, Alaska, flying north toward Barrow with the goal of exploring an unknown region of the Arctic Ocean north of Barrow. As they approached the mountains of northern Alaska, they climbed to an altitude of nine thousand feet before the *Alaskan* began to struggle. They passed between the mountain peaks and entered a dense bank of clouds around the point where their up-to-date United States Geological Survey (USGS) maps went blank. They flew through the clouds for almost two hours before breaking through into open air.[1]

Wilkins had been to the Arctic on foot before, but his view from the cockpit of the *Alaskan* was new to him. He saw large stretches of flat ice and watched as the ice got progressively rougher. “It was the ice of the Arctic Sea,” he noted, “I could tell that by the way the ice piled up in ridges like huge swaths of hay.”[2] Wilkins and Eielson had reached the coast much earlier than anticipated. Wilkins made note of flatter areas of ice that could be useful in case they needed to land. They pressed onward for over an hour and a half, deeper into the ice, even though they had clearly

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[1] George H. Wilkins, *Flying the Arctic* (New York: The Knickerbocker Press, 1928), pp 49-55.

[2] Wilkins, p 55

overshot Barrow. The opportunity that presented itself was irresistible. "So far as we knew, no man had been so far in that direction," Wilkins explained. "I was jubilant. We had actually started our work of exploration!"[3] He had not yet set foot on the ice of the Arctic Ocean, but Wilkins believed that the work of exploration had already begun with distant views of hay-stack ice.

Prior to Wilkins, the Arctic had long been a domain for exploration. Europeans tentatively ventured into the region by ship, sled, and foot—possibly as far back the classical voyage of Pytheas, in his search for the semi-mythical land of Thule. According to Strabo, Pytheas claimed that as he went farther north, the land, air, and sea melded into one indistinct substance.[4] As Wilkins and Eielson flew above the Endicott Range in Alaska, they encountered eerily similar conditions. "The light grey clouds with sunlit tops blended perfectly with the sky," Wilkins wrote. "We seemed to be the only speck in a boundless world. There was nothing for contrast and from which to judge space or distance; nothing in front of our eyes except the tapering bonnet of our engine; nothing below us to be seen but the same grey, grey

[3] Wilkins, p 56

[4] Strabo, *Geography,* 2.4.1.; Strabo's recounting of Pytheas' claim was that near Thule "neither earth, water, nor air exist, separately, but a sort of concentration of all these, resembling a marine sponge, in which the earth, the sea, and all things were suspended, thus forming, as it were, a link to unite the whole together."

mass. I am sure that we could find no situation more weird if we were to travel through space to the moon."[5]

Forty years later, Farouk El-Baz sat in an office in Washington, D.C., staring at picture after picture filled with the grey surface of the Moon. A geologist working for the lunar exploration team of Bellcomm, Inc., El-Baz was among the first people to closely scrutinize these photographs. The images came from the Lunar Orbiter spacecraft—a series of five robots that collectively spent over fifty days orbiting the Moon in 1966 and 1967. During these orbits, the Lunar Orbiter team used these robots to capture hundreds of high-resolution images of the lunar surface. Before El-Baz, scientists at USGS and other institutions had been sifting through these photographs, making note of various features and trying to explain them. Their primary goal was to find flat spots that might be usable for a landing.

These episodes occupy a strange place in the history of exploration, almost as indistinct and inscrutable as the grey Arctic mass described by Pytheas and Wilkins. They fit cleanly into some classic categories of exploration, but clearly defy others. Though Wilkins cast himself as the heroic explorer, he made his famous polar expeditions not by sled or ski, but from the relative comfort of a cockpit. Farouk El-Baz was not even in the cockpit of an airplane or a spacecraft, but in a government

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[5] Wilkins, p 53-54.

office. Were George Wilkins' trips by plane truly exploration? Was Farouk El-Baz an explorer at all? Or were they engaged in a completely new type of historical process enabled by twentieth-century technological developments? These questions are complicated by the self-perception of Wilkins and the twentieth-century scientists like El-Baz, who often placed themselves in a tradition of scientific exploration that stretched back centuries. The question of whether these episodes "count" as exploration may seem like a superficial or semantic question. But because of the relationship between exploration and other historical processes—such as settlement, conquest, and the exploitation of land and people—this question takes on real historical significance. The Lunar Orbiter program of 1966-1967 is an excellent case study for investigating this question.

The story of Lunar Orbiter is inseparable from the Apollo Program, which has had its history thoroughly documented and analyzed. Historians and other authors who write Apollo narratives often focus on the crewed landing missions that were the central goal of the program. The goal of landing on the Moon was famously articulated by John F. Kennedy in a 1962 speech at Rice University. It was a late and somewhat desperate gambit in the prestige-signaling competition of the Cold War—the "Space Race" that the United States was in many ways losing to the Soviet Union in the early 1960s. Some writers have compared the alignment of geopolitical competition with the ambitions of would-be explorers to similar convergences from the fifteenth century through the nineteenth. Narratives in books and documentaries have portrayed the Apollo astronauts as successors to the "heroic explorers" of these periods.

Robotic spacecraft, in contrast, have been covered largely as stories of institutional success and failure, as feats of engineering, or as relatively autonomous objects instrumental to some other purpose. In some works, they are treated as fairly straightforward scientific tools—pipelines for delivering images and data for scientific research. In other cases, robotic spacecraft are given a sort of agency of their own, written about as if "they" pointed their cameras at an object or performed some maneuver.[6] There is some truth to all these characterizations. But a deeper acquaintance with robotic missions also reveals them to be deeply human endeavors, with all the attendant struggles, drama, and complex decisions. The people who work on these missions are deeply aware of this fact, and often frame robots as having significance beyond being engineering marvels or straightforward scientific instruments. They consider robots to be a method through which humans engage in a more complex process of scientific exploration. Planetary scientists Carl

[6] Narratives of institutions and research pipelines are most apparent in NASA official histories, such as: Bruce K. Byers, *Destination Moon: A History of the Lunar Orbiter Program* (Washington, D.C.: National Aeronautics and Space Administration, 1976); Historian Stephen Pyne addresses the issue of robotic agency in his book: Stephen J. Pyne, *Voyager: Exploration, Space, and the Third Great Age of Discovery* (Penguin Books, 2011) Kindle.

Sagan and Jim Bell have emphasized this aspect of robotic exploration frequently when writing and speaking about it.

The human-oriented view of robotic exploration has not been neglected by people who study space exploration. Sociologist Janet Vertesi analyzed the human side of robotic missions to Mars in her book *Seeing Like a Rover*, the result of her taking on the role of a participant observer in the teams of the Mars Exploration Rover (MER) mission.[7] Historical studies of space exploration should also take this perspective into account, and some have started to do so.[8] When satellites and rovers are not treated simply as autonomous emissaries or inert instruments, but as imperfect attempts to extend our senses and perspective to other worlds, we reveal new types of stories. Participants in these missions speak about them in ways that convey a sense of travel—that they have been to different worlds, seen things never before seen, and reacted to unanticipated conditions. If we take them at their word, robotic missions may have a richer connection to the history of scientific exploration

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[7] Janet Vertesi, *Seeing Like a Rover: How Robots, Teams, and Images Craft Knowledge of Mars* (Chicago: The University of Chicago Press, 2015) Kindle.

[8] You can see this perspective conveyed clearly in Sagan's *Pale Blue Dot*, and Bell's *The Interstellar Age: The Story of the NASA Men and Women who Flew the Forty-Year Voyager Mission*. Bell also collaborated with astronomy historian William Sheehan to write *Discovering Mars*, which provides more of this perspective in the case of Mars exploration. Stephen Pyne also discusses this perspective in his work on Voyager. The work of Sagan, Bell, Sheehan, and Pyne provided much of the impetus to consider earlier episodes of robotic exploration in this way, as have conversations between Bell and the author.

than has so far been acknowledged. Paying attention to the robotic missions that preceded Apollo 11 reveals an important story running parallel to human spaceflight, with deep historical roots and long-lasting impacts on the process of scientific exploration.

Chapter 1: Scientists and Robots in the Apollo Program

1.1 The Need for Robots

The incentives created by the Apollo program led to an alignment of interests between groups that wanted to go to the Moon for very different reasons. The U.S. government needed a win in the Cold War competition with the Soviet Union. Scientists in the emerging field of planetary science wanted to travel to what was increasingly seen as a newly accessible scientific field site. It quickly became clear that these two groups needed one another to achieve their goals. For the U.S. government, scientists played an instrumental role in safely landing a person on the lunar surface and planting a flag. For early planetary scientists, the Apollo astronauts could become field scientists (or proxies for field scientists) immediately after the photo opportunity, able to perform "ground-truthing" in an existing project of scientific investigation. In the early days of Apollo, growing tension and interplay between these goals shaped the planning of the mission, and the relative weighting of human and robotic methods of exploration. One of the major reasons for the involvement of both scientists and robots in the planning process was the state of scientific knowledge about the Moon.

Very little was known for certain about the nature of the lunar surface in the early 1960s. This was a problem for the Apollo planners—at least one astronomer at

Cornell suggested that the lunar surface might not have enough structural integrity for landing. Geologists like Noel Hinners from Bellcomm didn't find this convincing in the slightest, but admitted that before early lunar probes like Ranger, scientists could not rule the idea out completely.[9] Other scientists speculated that the electrostatic properties of the lunar soil might cause it to stick to glass and other equipment, creating thick layers of dust that could prevent astronauts from seeing out of vehicles or space suits.[10] What was a problem for Apollo planners was an opportunity for scientists—researchers speculated about the answers to these questions, or conducted laboratory experiments to answer them. But despite their efforts, a great deal of uncertainty remained. It was clear that before sending people, NASA needed to investigate the conditions on the Moon more directly and in more detail. Planners and scientists often framed this investigation in terms of better understanding the "environment" which astronauts would be travelling through.

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[9] Noel W. Hinners, interview by Rebecca Wright, NASA Headquarters Oral History Project August 18, 2010, p 6.; The Ranger spacecraft preceded Lunar Orbiter—they were designed to impact the lunar surface.

[10] L.C. Van Atta, "Development and Test of a Lunar Surface-Transport Vehicle," in *A Review of Space Research*, National Research Council, (Washington, D.C.: The National Academies Press, 1962) https://doi.org/10.17226/12421. Chapter 4, pp 12-13.; Note: *A Review of Space Research* is an unorthodox document. It is divided into chapters, each with their own page numbering system, so citations here will refer to both chapter and chapter-specific page number. Much of the book has no named author or editor, and these sections will be attributed to the National Research Council. There are numerous appendices that have named authors, and there are special notes indicating that the opinions of these authors do not represent the opinion of all participants. These sections will be attributed to the individual author.

The need to gain this knowledge—and to do so quickly—created much of the initial impetus for robotic missions to the Moon.

In July 1962, Joseph Shea of NASA's Office of Manned Space Flight (OMSF) outlined his vision of the relationship between robotic and human spaceflight. He believed that the primary constraint on human expansion into space was an "understanding of this new, relatively unknown environment."[11] As Deputy Director of the OMSF, Shea's attention was on the data needed to successfully execute a crewed mission to the Moon, and he organized the environmental data into three broad categories: "1) cislunar and lunar environment, 2) reconnaissance and topography, 3) surface physical characteristics."[12] By this point, NASA had begun planning for the Surveyor project, which primarily involved a series of robotic spacecraft designed to land, to take pictures from the lunar surface, and to analyze the lunar soil.[13] These landers, combined with a proposed "Surveyor orbiter," would be able to provide data in all three of Shea's environmental categories, with photographic systems providing data in the second and third categories specifically. According to Shea, the point of this reconnaissance was to ensure that "the [crewed

[11] Joseph F. Shea, "Relationship Between the Manned and Unmanned Programs" in *Technology of Lunar Exploration*, ed. Clifford I. Cummings and Harold R. Lawrence (New York: Academic Press Inc., 1963), p 971.
[12] Shea, p 971.
[13] Giberson, W. E. "Surveyor Project Status" in *Technology of Lunar Exploration*, p 877-904; Also see Lund, p 50-51.

landing] mission will hold no surprises…for the astronauts."[14] This was to be accomplished with strict and precise requirements for the resolution of photographs and their content.

Historian Michael Robinson has noticed the frequent use of the term "environment" by those involved in space missions and identifies this concept as a key focus of space exploration in general.[15] He suggests "environment" as an alternative or replacement to the "frontier" model used in previous episodes of exploration. This seems accurate in the sense that both terms have been used to characterize new and relatively unknown places at the edge of an exploring culture's knowledge. However, in my reading of the examples presented here, the concepts of "environment" and "frontier" diverge in important conceptual ways. They may even coexist as independent characterizations of place in space exploration. Mission planners, engineers, and scientists seem to think of the environment in a very limited way—as the physical conditions that make a place unique. To them, a comprehensive understanding of this environment was an essential precursor to human travel. To the space explorers of the 1960s, understanding the environment was a necessary first step before turning a site into a frontier, which meant gathering as much information as possible to reduce "surprise."

[14] Shea, p 973.

[15] Michael F. Robinson, "Science and Exploration" in *Reinterpreting Exploration: The West in the World*, ed. Dane Kennedy (Oxford: Oxford University Press, 2014), pp 21-37.

On one hand, the desire to eliminate surprise makes it seem as though this episode of exploration was more controlled than those of previous eras, which were often full of surprises. But explorers in every era had sought to limit surprise, because with surprise came risk. To minimize risk, a type of limited but accessible aerial perspective was an important part of exploration in almost every era. Mariners climbed onto the masts or into the crow's nest to get a better look at the surrounding area, or to scout for land. Explorers trudged up hills and mountains to get a view of the area ahead of them before venturing forth into it. Sometimes their views from these vantage points were quite detailed and played an important role in their route-finding. On Thursday, April 25th, 1805, Meriwether Lewis described one instance in detail:

> "Knowing the river was crooked, from the report of the hunters who were out yesterday, and believing that we were at no very great distance from the Yellow stone River; I determined, in order as mush as possible to avoid detention, to proceed by land with a few men to the entrance of that river and make the necessary observations to determine its position…when we had proceeded about four miles, I ascended the hills from whence I had a most pleasing view of the country, particularly of the wide and fertile vallies formed by the missouri and the yellowstone rivers, which occasionally unmasked by the wood on their borders disclose their meanderings for many miles in the passage through these delightfull tracts of country. I determined to encamp on the bank of the Yellow stone river which made it's appearance about 2 miles South of me."[16]

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[16] Merriwether Lewis, journal entry, Thursday April 25th 1805, in *The Journals of Lewis and Clark*, ed. Bernard DeVoto (New York: Houghton Mifflin Company, 1953), pp 98-99.; transcribed as it appears in the text—Lewis was creative with his spelling and grammar.

The journals of the Corps of Discovery Expedition are full of such examples—on quite a few of their daily treks, Lewis and Clark and their companions knew exactly where they were heading because they had seen it from above.

If we consider robotic exploration to be a human-centric mode of exploration, we find that remote sensing technologies became a way to minimize the element of surprise more effectively, through more comprehensive and higher resolution aerial views. These views then played an important role in understanding the Moon both as a physical environment and as a destination. The teams behind Lunar Orbiter played the role of scouts on a larger mission of exploration. They forged ahead of the main party and climbed to the top of the hill to get a better look at the landscape. The techniques they used had roots in existing technological and scientific practices that used visual representation to better understand scientific objects. Through Lunar Orbiter, teams of scientists and engineers applied these practices to transform the scientific object of the Moon into a place accessible for travel.

1.2 Early Lunar Science and the First Lunar Probes

The goal of putting a spacecraft into orbit around the Moon was, ultimately, obtaining detailed views of potential Apollo landing sites. The planners of Lunar Orbiter ended up prioritizing image resolution over mapping for this reason, but mapping was still essential for understanding the topography of potential landing sites.[17] Attaining an understanding of topography required analysis of geomorphology, and the creation of theories about the geological history of the Moon. This meant trying to figure out the size of lunar features, the height of prominences, the depth of depressions—a process that went hand-in-hand with mapping these features consistently and accurately. This information could then be combined with data about radiation, strength of gravitational fields, and albedo of surface material to modify larger theories of lunar geological history. All this information was critical for planning a lunar landing. The Apollo mission planners—the Cold Warriors—needed the scientists. And the scientists were already interested in and investigating the Moon.

The scientists involved in this process were largely using practices based on Earth-based telescopic observation. In 1972, astronomer Zdeněk Kopal reflected on

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[17] The Boeing Company, "Lunar Orbiter I Photography," NASA Contractor Report (NASA CR-847), Washington, D.C., 1967, p 42.; Boeing 's contractor report on Lunar Orbiter I explains that lens choices were made that made mapping slightly more difficult in exchange for higher resolution pictures.

the previous two decades of lunar mapping efforts, a project in which he was a principal participant. In his description, we get the sense that by the launch of the first Lunar Orbiter mission in 1966, Earth-based telescopic observation was approaching a sort of zenith in its capability to provide useful information about lunar topography. Astronomers had used telescopic observations, mostly in the form of photographic plates, to create relatively accurate maps. Their goal was usually to create maps that could represent the precise locations of certain lunar features relative to other features. These maps could aid in the scientific analysis of the Moon's topography and geology, known as selenology. [18]

To create accurate and useful maps, lunar cartographers needed to produce a coordinate system. The cartographers experimented with different types of coordinate systems, but all used roughly the same techniques to measure features and assign coordinates to them. Astronomers used micrometers to measure the size of different surface features in photographs, or the length of shadows that could be used to calculate the height of features. They designated "control points" at certain positions and calculated the distance to other features from these points. Then they extrapolated these measurements across multiple images that were put together into

[18]Zdeněk Kopal and R.W. Carder. *Mapping the Moon: Past and Present*. (Dordrecht, Holland: D. Reidel Publishing Company, 1974), pp 1-146.

larger maps through a sort of mosaic process.[19] But the limitations of these methods surfaced quickly. In a paper published in *Icarus* in 1966, C.L. Goudas described the primary problems associated with producing accurate control positions for various lunar features.[20] He broke the problems down into three parts, the first being "the large distance between the observer and the Moon," which frustrated attempts to finely calculate the position of lunar features. The second problem arose from the variability of lighting conditions, which could change measurements made of surface features. The third problem was atmospheric distortion, which could lead to situations where "the same formation can be found at places up to 50 or more microns apart on two photographs taken within the same night, hour, or even minute."[21] Goudas made note of ways in which ground-based observers could compensate for these problems, but none of them were perfect. The problems of distance and atmospheric distortion are simply inherent to Earth-based observations of celestial objects.

Observations from a distance, while sometimes useful to scientific explorers in previous centuries, were equally limited. "During long sea-voyages," wrote Alexander von Humboldt, "a traveller hardly ever sees land; and when land is seen

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[19] Kopal and Carder, pp 61-71.
[20] Goudas, C.L. "The Current Status of Selenodetic Control Systems." *Icarus* vol. 5, no. 1 (New York, 1966), pp 316-317.
[21] Goudas, p 317.

after a long wait it is often stripped of its most beautiful products. Sometimes, beyond a sterile coast, a ridge of mountains covered in forests is glimpsed, but its distance only frustrates the traveller."[22] Telescopic observations of the Moon revealed sterile coasts of lunar "seas"—called mare—and lunar mountain ridges in some detail. But scientists needed to get closer if they wanted to understand the lunar surface better. They required higher resolution observation than was possible to acquire from the surface of the Earth. Somehow, they needed to travel closer to their subject.

In the 1950s and 1960s, they got their chance. The United States and the Soviet Union began sending robotic probes into space in the early stages of the Cold War, and knowledge produced using those probes became both justification for launching them and a source of prestige. The first robots that engineers from the United States sent to the Moon were the Pioneer and Ranger spacecraft. The Ranger probes were designed to impact the surface of the Moon, and engineers equipped them with six television cameras that automatically took photographs of the lunar surface during Ranger's precipitous descent. But the first Rangers failed, and it wasn't until 1964 that Ranger 7 successfully returned images from the Moon. The Soviet Union had already sent their Luna probes to Moon as early as 1959 and

[22] Alexander Humboldt, *Alexander Von Humboldt: Personal Narrative of a Journey to the Equinoctial Regions of the New Continent*, trans. Jason Wilson (London: Penguin, 1995), Kindle, p 7.

returned images—noisy and showing mainly vague splotches, but images nonetheless—by 1960.[23] In those liminal years of the early 1960s, scientists and government officials were anxious. They set their sights firmly on the Moon, and the urgency to get there intensified.

1.3 The Warriors, the Scientists, and the Engineers

In the summer of 1962, scientists from all over the United States convened at the State University of Iowa for eight weeks. The roster of attendees included names that are now plastered across the solar system, observatories, and NASA spacecraft: Van Allen, Kuiper, Shoemaker, Webb, Spitzer, Whipple, Drake, and Sagan. The Iowa Summer Study, as it came to be called, brought these scientists into direct collaboration with engineers and bureaucrats from government and industry. It was an important step in the beginning of an intensive collaboration between these groups that would become the model for space science in the twentieth century.

The Summer Study began in June, just a few months before John F. Kennedy's famous speech at Rice University describing why "we choose to go to the Moon." The planners of the study intended to create a direct line between NASA leadership and the scientific community—it was funded by NASA and organized through the

[23] Tom Lund, *Early Exploration of the Moon: Ranger to Apollo, Luna to Lunniy Korabl* (Switzerland: Springer Praxis Books, 2018), pp 6-22, 334-338.

Space Science Board of the National Academy of Sciences. The Summer Study was hosted in Iowa partly because it was the academic home of James Van Allen, who had established early and deep ties to the U.S. space program through his work on the Explorer satellites. Van Allen was chosen as chairman of the Summer Study. The goal of the Summer Study was to create a comprehensive report detailing current knowledge about space science and defining the most pressing problems in relevant fields. Signifying the true purpose of this whole endeavor, the capstone of the summer study was a series of summary briefings given to NASA administrator James E. Webb and a group of other NASA officials in August.[24]

NASA did not create this collaboration out of thin air. Scientists were already thinking about space exploration when they were approached by the Cold Warriors. A growing number of scientists were already thinking of the solar system as a place for field science. Earlier in 1962, many of these scientists came together to launch *Icarus*, the first journal of its kind dedicated to a newly emerging scientific field uniting "astronomy, geology, geophysics, meteorology, geochemistry, plasma physics, and biology."[25] This nascent research collective was never completely divorced from a spirit of exploration. In the inaugural issue of *Icarus*, the editors

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[24] National Research Council, *A Review of Space Research* (Washington, DC: The National Academies Press, 1962), Chapter 1, p 32

[25] Zdeněk Kopal and A. G. Wilson, "Preface," *Icarus* no. 1 (Amsterdam: Elsevier Science B.V., 1962), p i.

explained their choice of title, saying that while Icarus' story was "not exactly and auspicious beginning for the exploration of the solar system," it demonstrated the sort of boundary-pushing that the project of planetary science would require.[26]

The topics covered in *Icarus'* first issue were roughly duplicated by the Iowa Summer Study's program. The Cold Warriors had to appeal to the scientists and engineers, who had their own systems of organization and coordination in the form of universities, journals like *Icarus*, and corporations. By 1961, the relationship between NASA and the scientific academy seemed to be rocky. NASA had recruited a cadre of young scientists, and according to NASA historian Homer E. Newell, the established academic scientists believed that these young recruits "were not sufficiently seeking and heeding the advice of university scientists."[27] To achieve the goal of getting to the Moon, these groups had to cooperate, not only with each other but with the engineers and bureaucrats who held the keys to the entire endeavor. Coordination between NASA, the academy, and industry proved to be a complex problem. The endeavors of the burgeoning space program—like the Iowa Summer Study—often involved a dizzying array of collaborators and government offices, sometimes making it unclear who exactly was in charge or how the results of the

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[26] Kopal and Wilson, p ii-iii.

[27] Homer E. Newell, *Beyond the Atmosphere: Early Years of Space Science* (Washington, DC: National Aeronautics and Space Administration, 1980). Updated August 5, 2004, p 206.

collaboration would ever be used.[28] Many of the scientists in this mix considered themselves good patriots and were perfectly willing to be recruited to the aims of the Cold War. But they also had their own ambitions and goals, which would threaten to hamper their ability to provide NASA with exactly what the organization asked of them. This fact became clear over the course of the Iowa meetings.

In general, the Summer Study's format was intended to allow freedom for the scientists. The Space Science Board (SSB) outlined the goals of the study in the introduction of *A Review of Space Research*, the official summary of the proceedings. The participants were supposed to focus simply on "basic research in space." Ostensibly, the participants were not supposed to consider the Apollo program as anything other than a vehicle for this research, and according to the report Apollo "was considered in terms of its scientific potentials, because it will certainly eventually lead to a greater capacity for science in space."[29] But the opening address by Lloyd Berkner of the SSB seemed to undercut this freedom slightly. The first task of the study, he told the participants, was to "consider the future course of our nation's scientific program in space, and to help the government's planners chart the

[28] In the case of Lunar Orbiter, this involved many NASA branches and organizations, which often shifted during the planning process and had varying degrees of input and control over Lunar Orbiter operations. To simplify the narrative here, and because the focus of this work is mainly the perspective of the scientific and engineering communities, these will mainly be referred to simply as "NASA" unless the specific branch or subgroup is relevant.

[29] National Research Council, Chapter 1, p 1.

way." The second task was to aid "the government in its conduct of the space research program," for the purposes of "education, stimulation of industry and the nation's economy, research in many allied fields," and international collaboration. The third task was to create a bond between industry and the government, so that the industrial participants might understand "the many broad problems and decisions that must be faced by our government people."[30] Already, the conversation was to be filtered through national priorities, which at the time were clearly Cold War competition and the race to the Moon.

The tension between free academic inquiry and achieving government priorities became most obvious in the sessions on lunar science. In the outline of research sessions and their conclusions, the titles of most sessions were simply the name of the scientific field under discussion—but the title for the session on lunar science included a qualifying phrase: "with Special Emphasis on Support for the Apollo Mission."[31] The authors of the chapter on lunar science also included extensive opening remarks. Their remarks are, on the surface, diplomatic and straightforward. But the remarks also seem to reveal that the participant scientists approached this topic with their own priorities that did not necessarily match up with those of their government partners. Each sentence of the opening remark

[30] National Research Council, Chapter 1, p 2.
[31] National Research Council, Chapter 1, p 8.

reflects a different facet of the complex relationship between the collaborators, from the perspective of the Cold Warriors who directed the mission:

> "Discussions of [the Apollo program] revealed that there is considerable confusion about the Apollo Mission and its proper justifications… In the first place, the Apollo program is related to man's innate drive to explore unknown regions, to national prestige, and to national security. These elements are of concern not only to scientists but to all other segments of our society.
>
> In the second place, there are important scientific objectives in the Apollo program, and it is in terms of science and scientific opportunities that the program appears to have been most widely misunderstood…
>
> Put in the simplest terms, the objective of the Apollo program is to place a man on the Moon and return him safely. Thus the current program is primarily a technological and engineering effort, and this fact ought to be generally recognized…"[32]

The frankness of this introduction is a clear indication of the tension brewing between the warriors and the scientists. But the need to cooperate seems to have led to promises being made which would anticipate the trajectory of not only the Lunar Orbiter program, but the Apollo program itself. The opening remarks continued by suggesting a vision of the role that scientists and robots might play after the first lunar landing. Again, each sentence reveals important aspects of the Apollo planners' vision for space exploration:

> When it becomes clear, however, that these ends will be achieved, a strong scientific validity immediately follows. By his presence, man will contribute

[32] National Research Council, Chapter 1, p 21-22.

> critical capacities for scientific judgment, discrimination, and analysis (especially of a total situation) which can never be accomplished by his instruments, however complex and sophisticated they become. Hence, manned exploration of space is science in space, for man will go with the instruments that he has designed to supplement his capacities--to observe what is there, and to measure and describe phenomena in terms that his scientific colleagues will clearly understand…
>
> It must always be remembered that as the earlier phases of the Apollo program proceed, engineering for the craft and for man will always assume the highest priority and the engineers must be protected in their ability to do their jobs. As the engineering tasks are accomplished, however, scientific investigations and missions will also be phased into the program; and, as flexibility and sophistication are achieved, scientific investigations will become the primary goals…
>
> The proper exposition of these concepts by the federal government should go far toward allaying misunderstandings of the Apollo program which are currently prevalent among many members of the scientific community."[33]

The chapters on lunar science that followed the remarks seem to have been shaped by the conversations and tension that led to the inclusion of these passages. While the summary reports focus heavily on science, their content is heavily skewed toward the scientific information necessary to affect a safe landing on the lunar surface.

The scientists' recommendations for Apollo give us insight into their priorities and goals, as well as their attitudes toward robotic missions. Scientists fought for a presence on the first missions to the Moon: "Should a scientist (at least one) be a member of the first Apollo crew?" they asked, and answered

[33] National Research Council, Chapter 1, p 21-22.

"Emphatically, 'Yes!'"[34] They argued that this was because of the various advantages of a scientist-astronaut over a robot, specifically the lack of the need to be programmed. They valued the ability to adapt to conditions and opportunities on the surface. They very much wanted and expected scientists to be on the lunar surface as "scientist-explorers," and considered the many methods that could be used to extend field science to the Moon. One idea under consideration was to train non-scientist astronauts to do scientific work, or to follow the instructions of scientists on Earth. This type of astronaut was unsatisfactory to the scientists—they had to be "programmed," and would essentially become another remotely operated presence in the field.[35] The scientists wanted to be there. Even with the expectation that scientists would make up integral crew members of the first crewed lunar missions, study participants seemed aware that their government colleagues might not provide that chance, and so the scientists focused heavily on robotic missions that they believed would be essential precursors to in-person missions of exploration. Their conversations occurred around the time that discussions of an orbital probe were making their way through the NASA bureaucracy, and likely informed the planning and execution of the Lunar Orbiter program.

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[34] W.W. Kellogg, "Summary of Responses to Space Science Board Inquiry on Scientific Program for the Apollo Mission," in *A Review of Space Research*, National Research Council, (Washington, DC: The National Academies Press, 1962) https://doi.org/10.17226/12421. Chapter 11, pp 17-19.

[35] National Research Council, Ch 11, p 1-17.

1.4 Engineering an Orbiter

The Summer Study participants focused heavily on the status of scientific knowledge about the Moon, especially as that knowledge was useful for reducing the hazards encountered by a landing attempt. Despite the history of telescopic study and the probes already sent by the U.S. and the Soviet Union prior to 1962, useful scientific knowledge seems to have been limited. The authors of the report indicated that only the Soviet probe Lunik III had given substantially new information, in the form of pictures from the far side of the Moon and indications that the Moon lacked a magnetic field.[36] Because of this ignorance, the study participants vigorously advocated for the acceleration of robotic missions, and for these efforts to be more tightly integrated with planning for Apollo. They wrote that the "acquisition of information about the lunar environment and surface must be accelerated if responsible engineering decisions are to be made in time for a successful manned lunar landing and return," before concluding that "closer collaboration between NASA's manned and unmanned programs is essential if the Apollo design information is to be obtained in time and if it is to be properly utilized."[37] Part of their reasoning for placing emphasis on the robotic probes was the

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[36] National Research Council, Chapter 4, p 1.
[37] National Research Council, Chapter 4, p 2-3.

urgency of getting information due to the timeline imposed on them by the Cold War priorities.

Design changes to the Apollo mission plan also changed the type of information gathering scientists recommended prioritizing. Not long before the Summer Study, the design of the Apollo mission had been altered to include a rendezvous in orbit around the Moon. This meant that scientists required more information about the lunar gravitational field, which could potentially vary enough to impact the orbits of Apollo spacecraft. Beyond gravitational information, most of the knowledge they sought had to do with lunar surface conditions. "Absolutely essential to designing for the Apollo mission," the report read, "is information concerning the hazard due to extreme surface roughness, the hazard due to deep or electrostatically-charged dust or to extreme surface crushability, and the hazard due to shrapnel-like secondary fragments from meteorite impacts."[38] Because of this, the report concluded that high-resolution photography should given top priority for uncrewed missions. The report placed special emphasis on mapping, and authors frequently refer to maps already produced by the Air Force and the United States Geological Survey (USGS) and discuss the need for new and more detailed maps.[39]

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[38] National Research Council, Chapter 4, p 3.

[39] National Research Council, Chapter 4, p 3-6; The Air Force maps were produced through the Aeronautical Chart and Information Center (ACIC). To reduce the number

Because of these requirements, the section on lunar science included an extensive discussion of lunar photography. The reports on this topic came primarily from the industry-associated engineers that participated in the Summer Study.

There were two primary concerns regarding an orbital photographic mission: the resolution of the photography and the quality of the information contained in those photographs. Engineers at the Summer Study tackled the question of whether vidicon tube television systems or traditional chemical photography would be best, given these priorities. In his write-up on lunar photography, Sidney Sternberg of RCA considered the capabilities of these two technologies with regards to resolution and grey levels, particularly relevant for their ability to provide information about surface characteristics.[40] He believed that given the state of vidicon tubes, it was "highly unlikely that chemical photographic film returned to the Earth after circling the Moon will add any new information not available from a television impactor about the physical form of the Moon's surface material."[41] When it came to resolution capable of revealing topography and distinguishing surface features of

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of acronyms and maintain readability, this paper will mainly refer to ACIC as the "Air Force" unless a distinction is relevant.

[40] When analyzing lunar photographs, being able to distinguish where shadows ended was crucial to methods of selenography, making grey levels an important metric. See Kopal and Carder.

[41] S. Sternberg, "Lunar Photography," in *A Review of Space Research*, National Research Council, (Washington, DC: The National Academies Press, 1962) https://doi.org/10.17226/12421. Chapter 4, pp 18.

the required size, however, other study participants made the case that chemical photography should be seriously considered.

William Kellog from the Rand Corporation and Leo Steg of the Space Science Laboratory at General Electric addressed the engineering problems involved in creating a complete spacecraft system capable of delivering the highest resolution images possible. Kellog and Steg spent a great deal of their report talking about one of the most important considerations to any aerospace engineer: weight. TV systems required a transmitter, assumed to be around fifty pounds, in addition to the primary camera equipment. But systems using chemical photography were assumed to be equally heavy, if not heavier than the total weight of a TV system. In the end, their evaluation suggested that when deciding between TV and chemical systems, "the selection would not be clear."[42] However, their estimates were based on two major assumptions about these imaging systems.

First, the weight for a TV camera capable of this resolution is listed as being "150(?)" pounds, with the caveat "to be developed."[43] So the true ability for TV systems to deliver the required resolution in a timely fashion seems to have been in doubt. Second, the weight equivalence Kellog and Steg arrived at was partly due to

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[42] Kellogg, W. W. and L. Steg, "Pictures of the Moon," in *A Review of Space Research*, National Research Council, (Washington, DC: The National Academies Press, 1962) https://doi.org/10.17226/12421, Chapter 4, p 20.
[43] Kellog and Steg, Chapter 4, p 20.

an assumption about the nature of using chemical photography in space. Kellog and Steg (along with the other engineers in Iowa) assumed that the photographic film would have to be returned to Earth from orbit around the Moon before processing it chemically. This meant that much of the weight in their estimation – at least 100 pounds—came from the system for returning a capsule of film from lunar orbit and recovering it safely.

This strategy of chemical photography from space was already being practiced at the time, so it was a logical assumption. Kellog and Steg mentioned that the "recovery of capsules from satellites is now routine," and referred specifically to the "Discoverer" satellites which used that technique. Then they described how the decision to use this type of system at the Moon would be complicated by the fact that heat from reentry after return from lunar orbit would be higher.[44] The need to recover chemical film also would have meant significant time lag before the film could be processed, distributed, and analyzed. Kellog and Steg were not convinced that these problems gave the advantage decisively to TV systems, but mention that "these considerations have led to the tacit assumption that television is the only feasible way to get pictures from an unmanned lunar orbiter."[45] What they and their colleagues did not seem to know was that while they were discussing this problem,

[44] Kellog and Steg, Chapter 4, p 22.
[45] Kellog and Steg, Chapter 4, p 20.

new techniques had been invented and were being used that would change the calculus completely. In Rochester, New York, Eastman Kodak had created a system for returning chemical photographs from space without the need physically to return the film. Outside of Eastman Kodak, only a select few of the Cold Warriors were aware of it.

Chapter 2: Eastman Kodak's "Pre-invented" Lunar Camera System

2.1 Kodak Goes to War

The "Discoverer" spacecraft that Kellog and Steg referred to in the Iowa Summer Study were the public face of the classified CORONA satellite surveillance project. CORONA was one part of a larger project of satellite surveillance that the United States was pursuing from before the launch of Sputnik in 1957. The spy satellites used camera systems with the codename "Keyhole" to obtain high-resolution photographs over military targets, and the film was returned to the Earth using capsules that were caught midair by recovery planes. These techniques were designed to replace the U2 reconnaissance plane, creating a safer, more covert, and more efficient means of intelligence gathering. The holy grail of a satellite imaging system, however, was real-time imaging at high resolution.

In the late 1950s, the Air Force had attempted to achieve this feat through the SAMOS Project. Declassified information about this period has revealed that an Air Force partnership with Eastman Kodak achieved a degree of success, even before CORONA satellites launched. Kodak developed the E-1 and E-2 camera systems for SAMOS, which used specialized techniques to develop chemical film without reservoirs of liquid chemicals, scan the images on the developed film, and transmit those images over radio frequencies directly from orbit. It was hoped that this might get the United States closer to near-real-time imagery from SAMOS satellites.[46] Although many at the time were not aware, the E-1 eventually became the basis of the camera system for Lunar Orbiter. It was the result of a long history of partnerships between Eastman Kodak and the United States military that gave Kodak the technological experience to create such a system. A combination of Kodak historical collections and declassified documents—including internal CIA and Air Force histories declassified as recently as 2018—give us a better picture of the history behind the Lunar Orbiter cameras.

The Kodak press office was eager to use this history and their involvement in the space program as a marketing tool, publishing stories in the popular press about the history of their Moon cameras. These were largely exultant narratives, meant to demonstrate how innovative and forward-looking Kodak was while establishing the company as reliable and patriotic. In 1967, Kodak helped create a narrative detailing how they "pre-invented" the Lunar Orbiter camera system.[47] The basic narrative of "pre-invention" mostly follows the actual history of the technologies involved,

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[46] Cargill R. Hall, *SAMOS to the Moon: The Clandestine Transfer of Reconnaissance Technology Between Federal Agencies* (Office of the Historian, National Reconnaissance Office, October 2001), p 1-4.

[47] "Kodak Pre-Invented Moon Camera," Rochester Times-Union, February 3, 1967. and "How Kodak 'Pre-Invented' the Lunar Orbiter Camera (Based on an Article in the Rochester Times-Union February 3, 1967)", both in Kodak Historical Collection #003, D.319. Legacy, Rare Books, Special Collections, and Preservation, River Campus Libraries, University of Rochester.

despite placing possibly undue emphasis on Kodak's role in this history. It also leaves out a large portion of the pre-invention story that was hidden from the public. But these pieces and internal Kodak documents can still give us some insight into how they were able to assemble a remote transmission, film-based imaging system when many engineers at other companies seemed to think it was out of reach.

The story involves a small collection of existing technologies that made Kodak's camera system possible, almost all of which were developed before the late 1950s. First was specialized film, with the right size and sensitivity to take high resolution photographs from a great distance. Next was a mechanism for image motion compensation (IMC), the ability to make adjustments that could cancel out any movement of the camera system and avoid "smeared" images on the film. Then there were the mechanisms to store undeveloped film in a compact space and develop it. And finally, there were the tools to transmit images on the film remotely to receiving stations.[48] Nearly every one of these technologies solved problems that existed before space travel. They are the same problems that confronted engineers in the early twentieth century who worked on taking pictures from a moving airplane.

[48] See Byers and The Boeing Company contractor reports on Lunar Orbiter I, II, and III Photography. The term "smear" is used frequently in both and refers to a blurring effect with a directional orientation resulting from spacecraft motion, which the IMC was designed to prevent.

One of the first major applications of airplanes was wartime reconnaissance, and it did not take long for early aerial spies to bring up small cameras with them. Some of the first shots from an airplane in World War I were probably fired off by a camera operator. The earliest use of firearms from airplanes in the war was likely meant to discourage these photographic excursions. During the war, Eastman Kodak contributed a great deal of effort to refining photographic equipment for aerial photography, often through direct collaborations with the United States military. [49] Their involvement was in large part driven by the patriotic fervor of George Eastman himself. According to Kodak employee Burke Davis, Eastman gave his research laboratory the go-ahead to provide "any assistance it could for the prosecution of the war" in 1917.[50] By 1918, a brand new department within Eastman Kodak was created specifically for the purpose of developing new technologies that could assist in the war effort. [51] Rochester, New York—the headquarters of Kodak—even became the

[49] "Aerial Photographic Reconnaissance Techniques to Extend the Photographic Day," October 1958, and "Kodak Contributions to Aerial Photography", both in Kodak Historical Collection #003, D.319. Legacy, Rare Books, Special Collections, and Preservation, River Campus Libraries, University of Rochester; Denis Cosgrove and William L. Fox, *Photography and Flight*. (London: Reaktion Books Ltd, 2010), pp 34-35.
[50] Walter Clark to Burke Davis, copy of letter, May 26, 1966, Kodak Historical Collection #003, D.319. Legacy, Rare Books, Special Collections, and Preservation, River Campus Libraries, University of Rochester, p 1.
[51] Clark to Davis, p 2.

site for one of the Army's first aerial photography training grounds in 1918. The school operated for less than a year but may have graduated around 2,000 students.[52]

Interest in aerial photography continued into World War II, supported in part by continued military collaboration with industry. It was during this time that many of the technologies that made their way into the Lunar Orbiter were invented and improved. The necessities of war incentivized higher altitude photography to limit danger from enemy combatants, but high-altitude photography came with challenges. Aelred A. Koepfer was an engineer with the Air Force who worked on some of the technologies designed to tackle these problems. Koepfer received a patent in 1945 for his "Aerial Photographic Image Motion Compensating System." He was trying to solve a "blurring effect" produced by the motion of aerial cameras at high altitude, which was "directly proportional to the velocity of the associated aircraft and inversely proportional to the altitude." His solution was to pull the film across the focal plane of the camera "at a rate determined by the velocity and altitude of the aircraft."[53]

Koepfer also tracked progress in photogrammetric analysis, for determining detailed information about objects on the ground. He described one instance in

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[52] The exact number of graduated students was marked as uncertain in Clark to Davis, p 3.

[53] Aelred A. Koepfer, 1945. "Aerial Photographic Image Motion Compensating System." US Patent 2,424,989, filed September 13, 1945, and issued August 5, 1947, p 1.

which the height of a seawall in Okinawa was calculated to within two inches based on stereoscopic photography. The actual height was verified by American troops who took control of that particular beachhead—an early instance of what would become known as "ground-truthing" by those who work with remote sensing technologies.[54] Koepfer had a deep understanding of these technologies and their potential. In a 1959 talk covered very briefly by the *New York Times*, Koepfer speculated about how these techniques could be applied to satellites. He described the capsule return of film, but also mentioned that images from film could potentially "be transmitted to the ground by a television-like process." He also pondered a future in which satellites like this would become "excellent vehicles for mapping the Earth and the planets."[55] Considering the history of these satellites and the involvement of the Air Force in their development, this may not have been pure speculation. Regardless, his remarks caught the eye of someone at Kodak, and a clipping of this article ended up in the Kodak Historical Collection at the University of Rochester.[56]

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[54] Aelred A. Koepfer, "Development in the Field of Aerial Photography," *Photogrammetric Engineering* 12, no. 4 Dec. 1946, p 401.

[55] "Expert Envisions US Space Camera," undated, Kodak Historical Collection #003, D.319. Legacy, Rare Books, Special Collections, and Preservation, River Campus Libraries, University of Rochester; Appears to be from a NYT article published in 1959

[56] I could not find any evidence that Koepfer ever worked directly with Kodak. But given the involvement of Kodak in Air Force-related projects, it seems possible that there was

While Koepfer was working on IMC during World War II, Kodak continued to work on film and camera systems for aerial photography. The company's work continued into the Cold War. In October 1956, Kodak added a new department dedicated exclusively to aerial photography.[57] Kodak press releases and communications at the time talk about this decision and their research very obliquely. A paper by Kodak engineer Raife Tarkington described the purpose of the new department as insuring that "progress made in photography is applied as expeditiously as possible to existing aerial and military problems," and "to anticipate future requirements so as to direct efforts toward a solution."[58] The author of a 1962 *Kodakery* article mentioned the visit of two NASA officials, and their discussion of "some classified research projects" with Eastman Kodak vice-president Henry Yutzy.[59] In the Rochester *Times-Union* "Pre-Invention" article, director of R&D Arthur Simmons was interviewed, saying that "no one walked in and asked us to develop a camera and film system to take closeup photos of the moon," and went on to say that "Kodak has, for want of a better word, a 'library' of hundreds of

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direct collaboration. If Koepfer's remarks were not speculation, he may have been revealing classified information.

[57] R.G. Tarkington "Research and Development on Aerial Photography in the Kodak Research Laboratories" October 1958, Kodak Historical Collection #003, D.319. Legacy, Rare Books, Special Collections, and Preservation, River Campus Libraries, University of Rochester, p 1.

[58] Tarkington, p 2.

[59] "Photography Vital in Moon Shot," Kodakery 1962, Kodak Historical Collection #003, D.319. Legacy, Rare Books, Special Collections, and Preservation, River Campus Libraries, University of Rochester.

‘conceptual ideas’ which we don’t advertise.”[60] Each of these individuals was dancing carefully around the fact that Kodak was actively working on extremely sensitive military projects in the late 1950s.

2.2 Early Satellite Camera Systems

One of these was the CORONA program, which was relatively well-known to the public, although the full nature of the program remained hidden. Kodak was tasked with the processing of the capsule-returned film from this project at their “Hawkeye” facility in Rochester.[61] Launched on August 18, 1960, Discoverer XIV marked the first time the CORONA system worked fully as intended. Film aboard the Discoverer spacecraft was loaded into a capsule while in orbit, after which the capsule descended through the atmosphere and was caught in midair by a plane. The capsule was taken to Moffet Naval Air Station and discretely swapped with a dummy capsule that was then visibly shipped from the station. The real capsule was secreted away in an unmarked container and shipped to Rochester for processing at Hawkeye. This was a complex system, with a lot of room for error and a significant

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[60] How Kodak ‘Pre-Invented’ The Lunar Orbiter Camera, p 1.

[61] National Reconnaissance Office, “National Reconnaissance Office Review and Redaction Guide for Automatic Declassification of 25-Year-Old Information: Version 1.0, 2006 Edition” (NRO Classification Guide, 2006) https://archive.org/details/nro-review-and-redaction-guide/NRO%20Review%20and%20Redaction%20Guide%202006/, p 58.

delay before useful information could be retrieved.[62] Officials in the Air Force hoped that CORONA would be superseded by a more experimental method of satellite surveillance, which was being tested by the SAMOS program.[63] The existence of SAMOS also became known the public, but coverage in *Scientific American* as late as 1962 did not mention one of the more significant features of SAMOS that was being kept under wraps: the attempt at near-real-time retrieval of images.[64]

Declassified documents now allow us to track the development of this system. In October 1956, the United States Air Force issued a contract to the Lockheed Aircraft Corporation for the WS-117L program, the precursor to SAMOS

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[62] Robert Perry, *A History of Satellite Reconnaissance: Volume I – CORONA.* Prepared for the National Reconnaissance Office. (BYE 17017-74, HQ Air Force Special Project Production Facility, revised October 1973 from earlier drafts of 1964, 1967, and 1972, approved for release September 2018.) https://www.nro.gov/Portals/65/documents/foia/docs/HOSR/SC-2017-00006a.pdf; There is another version of this document that was declassified in May 2012, marked "copy 3 of 5." The 2018 document is marked "copy 1 of 5," and was the version used for this thesis; The first attempt at a "dress rehearsal" for this plan went comically awry, almost to the point of being suspicious. The courier tasked with transporting the capsule disregarded their instructions completely—despite "frantic protests"—then opened up the capsule on the way to delivering it directly to Air Force General Schriever. Perry, p 98.

[63] Perry, History Vol I, p 96-99.

[64] The public knowledge of SAMOS was partly accident and partly by design – Eisenhower wanted satellite development to appear completely peaceful. Knowledge of both programs leaked to the press early. SAMOS was overtly for reconnaissance, and it became a smokescreen for the true nature of the CORONA project. See Perry, History Vol IIA, 29-30.

and CORONA.[65] The principal subcontractor for the "Visual Reconnaissance" in the Lockheed contract was Eastman Kodak.[66] It seems likely that the department mentioned by Tarkington was created specifically for the purpose of this contract, considering it was created in the same month that this contract was issued. It was for this contract that Kodak created the E-1 and E-2 camera systems, which were capable of transmitting images from film for "read out" at ground stations.

This type of transmission and read out system not only seemed more efficient, but to some engineers in the very early history of spaceflight it also seemed more feasible. During the 1950s, there was uncertainty about whether any type of payload could even survive reentry through the atmosphere. That it could was not proven empirically until 1957, a year after the SAMOS contractors began seriously pursing read-out.[67] Recovery systems gained traction afterward (especially through CORONA), but for the time being the SAMOS group continued pursuing remote transmission. The early E-series cameras worked by using a type of electronic

[65]Kenneth E. Greer, "Corona," *Studies in Intelligence*, supplement, no. 17 (Spring 1973): p 1-37, in *Corona: America's First Satellite Program*, ed. Kevin C. Ruffner (Washington, D.C.: History Staff, Center for the Study of Intelligence, Central Intelligence Agency, 1995), pp 3-39; Lockheed Aircraft Corporation, Missile Systems Division. "Advanced Reconnaissance System: Weapon System 117L" (Summary LMSD-2903, March 1958), p 3; These sources also indicate that the WS-117L program was a larger project, with roots in 1946 feasibility studies by the RAND Corporation regarding satellites more generally. General Operational Requirement No. 80 made satellite surveillance a priority of the program in 1955. The surveillance aspects of this program were spun off into SAMOS.
[66] Lockheed, Weapon System 117L, p 5.
[67] Perry, History Volume IIA, p 5-6.

scanning system that resembled television in certain ways. First, film was developed by pressing it against a separate roll of "web," which was infused with the necessary development chemicals.[68] After processing, an electron beam was directed through the film. The density of the film varied across the exposed image, and that changing density altered the intensity of the beam. The beam was caught again on the other side of the film, and directed into a photomultiplier tube that converted the light into electronic signals based on the intensity of the beam. Engineers received those signals at ground stations where their equipment reassembled images based on the electronic signals. It was a clever recombination of existing technologies.[69] The equipment and the operation sequence were illustrated in Air Force documents, seen in Figures 1 and 2 below.

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[68] The role of the "web" mentioned in the declassified histories was filled by specially developed bi-material film created by Kodak and named "Bimat." It's unclear to the author if the web is actually Bimat, or a different, precursor material.
[69] Perry, History Volume IIA, p 11-12.

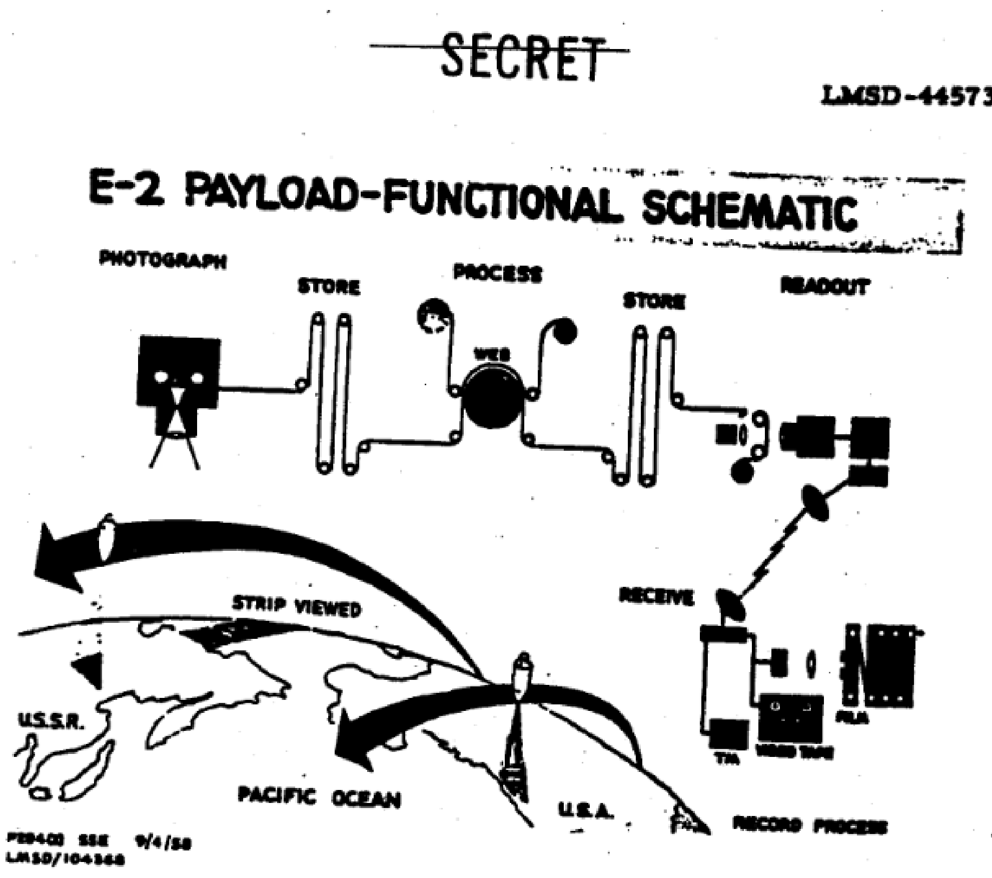

Figure 1: Schematic of the E-2 camera system. Shown in a Lockheed Aircraft Corporation briefing for the Air Force. The illustration is dated 1958 in the bottom left corner.[70]

[70] Lockheed Aircraft Corporation, Missiles and Space Division. "LMSD Satellite Systems Briefing. Part II. The SAMOS Program." (Briefing for Air Force Ballistic Missile Division, LMSD-445737, September 1959), p 9

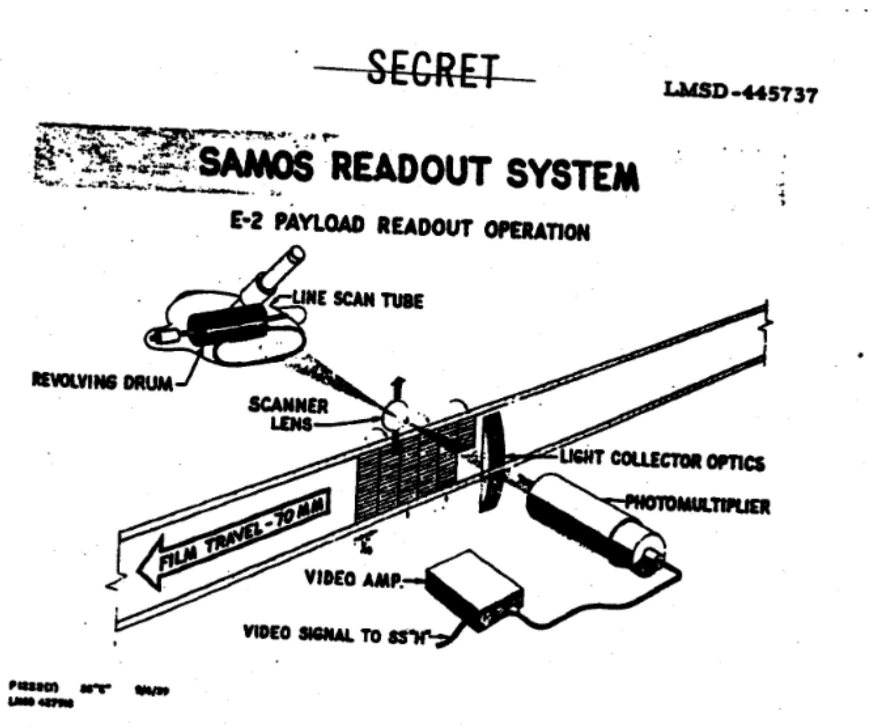

Figure 2: An illustration showing the scanning and "readout system" in the E-2 camera. This system was used to transmit images on the film to ground stations.[71]

Even so, the system was not perfect. The transmission and reconstruction process proved complex and slow given the early state of the technology, and transmission could only occur when the spacecraft was in view of ground stations, limiting its ability to provide near-real-time imagery.[72] Resolution was also an issue—the hope was that the E-2 could resolve objects about five feet in diameter. But it nearly missed getting its chance to demonstrate this capability, as the read-out

[71] Lockheed Aircraft Corporation, Weapon System 117L, p 21.
[72] Perry, History Volume IIA, p 10-14.

system faced off against internal opponents within the program. Lockheed remained optimistic about the advances happening with the read-out system, however, and development continued.[73] Meanwhile the newly created ARPA began exerting influence on the program, creating institutional confusion that seemed to suffuse the entire space program.[74] In the end, SAMOS was transferred to an office in the Department of Defense that became the National Reconnaissance Office, and the program fizzled. Despite its flaws, flight tests of the E-series cameras in 1960 and 1961 meant that during the Iowa Summer Study, Kodak was sitting on flight-proven technology that would become key to the development of a lunar orbiter.[75]

2.3 Kodak Joins Lunar Orbiter

In 1962, amid urging from the academy and increasing urgency from the Kennedy administration, NASA pressed forward in the development of a lunar orbiter. The original plan was to put TV cameras on an orbiting version of the Surveyor spacecraft.[76] But it became clear quickly that the Surveyor program would be unable to take on the additional task of creating a new type of spacecraft. So,

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[73] Perry, History Volume IIA, p 23-4.
[74] Perry, History Volume IIA, p 16-19.
[75] Hall, p 1-4.
[76] J.D. Burke, "Ranger Project Status" in *Technology of Lunar Exploration*, ed. Cliffford I. Cummings and Harold R. Lawrence (New York: Academic Press Inc., 1963), p 858.

NASA officials initiated the process of soliciting proposals for a new spacecraft design. In 1963, NASA began the final assembly of what would become the Lunar Orbiter program, sending out the final Request for Proposals in August.[77]

NASA received bids from a few of the usual players in the aerospace industry, and most included some sort of TV system like those that adorned Pioneer and Ranger. Lockheed submitted a proposal, but their rival Boeing had managed to snag Eastman Kodak as their main photographic subcontractor. It turns out that Kodak had to seek permission from the NRO before joining Boeing's project, because their bid included a system that was essentially the E-series camera that was used for SAMOS.[78] In August 1963, an agreement was arranged between the Department of Defense, the CIA, and NASA, signed by Robert McNamara and James Webb, that authorized NASA to use NRO reconnaissance technology.[79] In the end, NASA officials deemed Boeing's bid most likely to achieve the mission objects with an acceptable degree of reliability. Their decision was in large part based on the

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[77] Byers, p 47.
[78] Hall, pp 1-3.
[79] National Reconnaissance Office, "Subject: DOD/CIA/NASA Agreement on NASA's Reconnaissance Program" (Declassified document BYE-6789-63, August 1963, Declassified June 2013); Hall, pp 1-3.

strength of Eastman Kodak's photographic system, and how well it was suited to the mission requirements. [80]

For Apollo site selection, planners wanted to be able to see objects as small as one meter and discern slopes of less than seven degrees. NASA planners worked directly with the USGS and private research company Bellcomm to establish these parameters and evaluate hardware.[81] The requirements were seemingly mundane and technical, but they reflected a historically significant aspect of the Lunar Orbiter mission. The meter and slope requirements were put in place to find obstacles and terrain that might prohibit the touchdown of a crewed lander. These requirements placed Lunar Orbiter in a unique position within the history of space exploration, shared only by Surveyor—these missions were specifically designed to prepare the way for imminent human travel.[82] This was not true for Ranger or Pioneer, nor was it true for any other spacecraft after the Apollo era. The Kodak cameras were an important enabling factor that allowed the NASA requirements to be met within budget and on time.

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[80] Byers, pp 53-74.

[81] Byers, pp 13-18.

[82] There is an argument to be made that Lunar Orbiter sits in this category alone. Surveyor was eventually given over to Apollo preparations, but the program was initiated before Apollo materialized. See Byers, pp 9-11.

The Kodak engineers created a camera system that was capable of that resolution and could even exceed it. Their final system was a heavily modified and refined E-series camera from SAMOS. Kodak engineers swapped out the lenses and shutter systems for ones more suited to NASA requirements—resulting in the ability to take a medium-resolution and high-resolution exposure on the same film strip. They utilized the technique of moving the film across the focal plane for image motion compensation, using a velocity over height (V/H) sensor to gather the data required for that strategy.[83] Camera mechanisms pressed exposed film against Kodak's Bimat film for development and then dried the film on a heated drum. A line-scan tube shot an electron beam through the film, and a photomultiplier transformed the varying intensity of the beam into signals that could be received by ground station operators.[84]

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[83] The E-series cameras used a similar V/H sensor, but had an alternative type of shutter mechanism that used this information in a slightly different way. See Lockheed Aircraft Corporation, Weapon System 117L, p 41. In Figure 2, the "strip viewed" label shows this alternative shutter system in action, which allowed the system to capture continuous images across a long strip of film. This was a technique frequently used in aerial photography. The Lunar Orbiter cameras captured two discrete frames at a time, rather than creating a continuous image.

[84] The Lunar Orbiter process is described in detail through many Kodak and NASA publications. This description relies mainly on The Boeing Company, Lunar Orbiter I, pp 5-6; Byers, pp 122-123; and a collection of articles and press releases found in boxes 78 and 79 of Kodak Historical Collection #003, D.319. Legacy, Rare Books, Special Collections, and Preservation, River Campus Libraries, University of Rochester

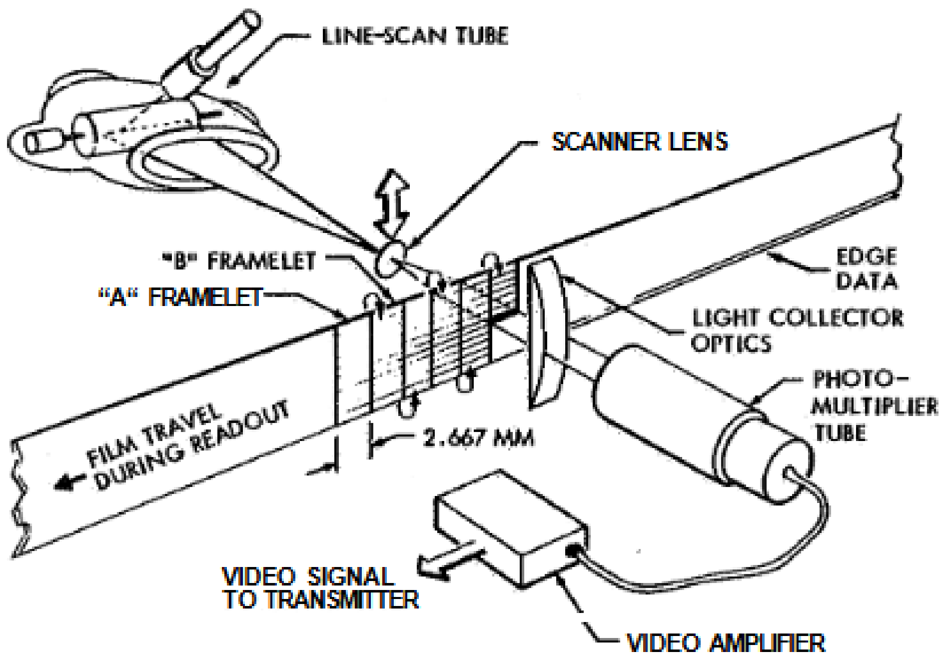

Figure 3: Illustration of Kodak's film scanning and readout system. From Boeing's Lunar Orbiter I Photography contractor report.[85] The illustration seems to be a lightly modified version of Lockheed's 1958 E-2 illustration, seen Figure 2.

[85] Boeing, Lunar Orbiter I, p 6

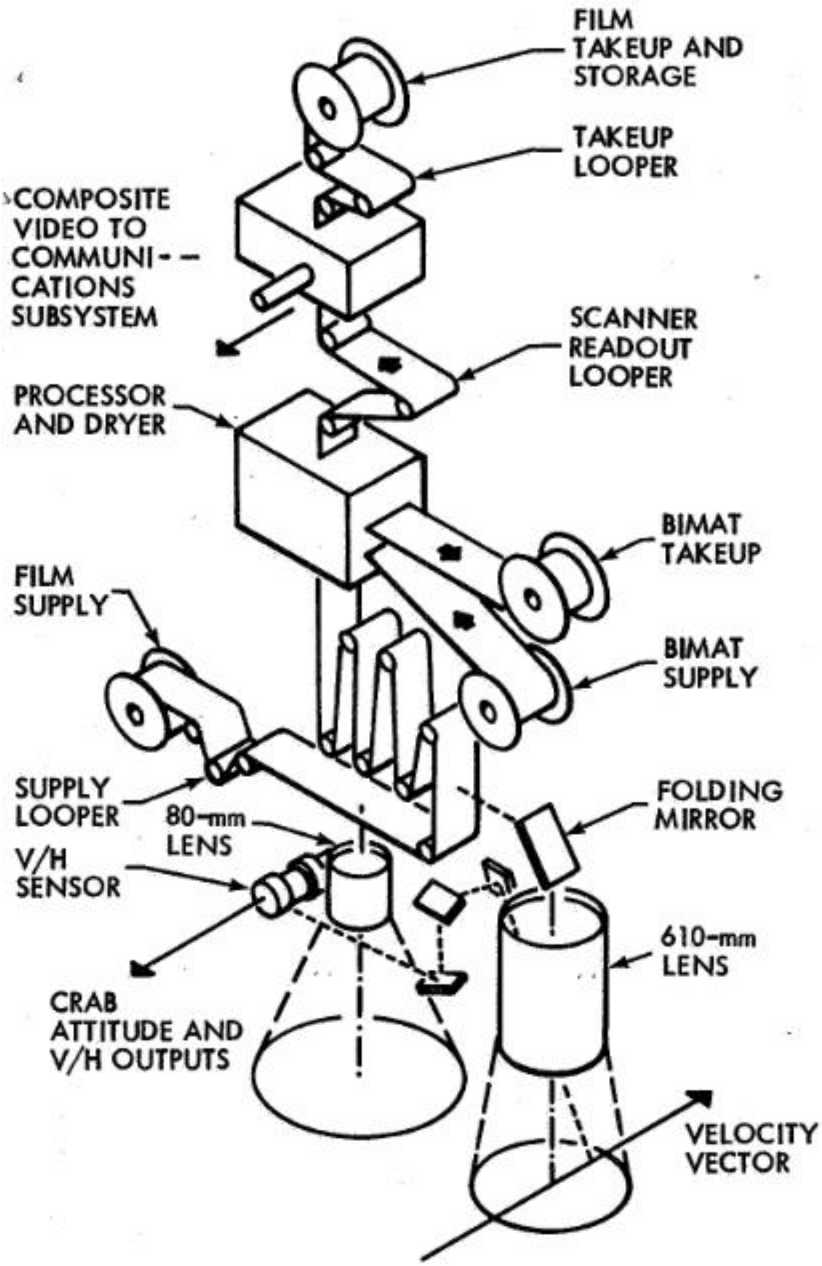

Figure 4: Illustration of Kodak's camera system from Boeing's Lunar Orbiter I contractor report.[86] The overall schematic is very similar to that in Lockheed E-2 illustrations, seen in Figure 1. The lens and shutter systems were the most significant modifications.

[86] Boeing, Lunar Orbiter I, p 3

The spacecraft designers took existing environmental knowledge into consideration, especially because radiation was particularly dangerous for the 70mm Kodak aerial film. A low film speed and special shielding around the camera system helped limit the potential danger of radiation exposure.[87] After scanning, operators in ground stations collected "framelets" that were 2.67mm long. Ground reconstruction electronics reassembled the image and displayed it on a kinescope tube, which was recorded by a 35mm camera. After processing at the ground stations, the team sent the 35mm film strips to Kodak in Rochester. Kodak teams completed reassembly by hand, resulting in 9 inch by 14 inch "subframes" that formed one part of a complete photograph.[88] This reconstruction process is the reason for the characteristic striped appearance of Lunar Orbiter photographs, and an illustration can be seen in Figure 5 below.

[87] The Boeing Company, Lunar Orbiter I, p 5.

[88] These photographs required 3 subframes. See The Boeing Company, Lunar Orbiter I, pp 6, 34.

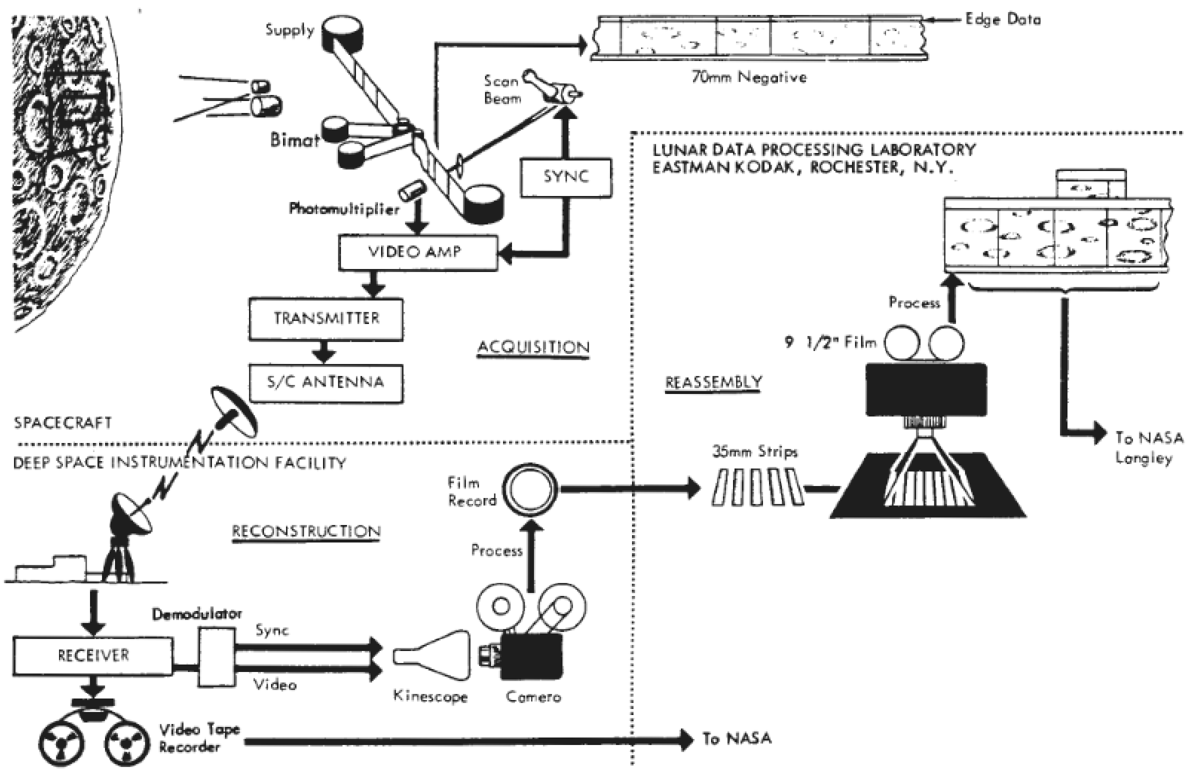

Figure 5: Illustration of "Data Acquisition, Reconstruction, and Assembly." From Boeing's contractor report on Lunar Orbiter III photography.[89]

Kodak then sent the final reconstructed photographs from Rochester to NASA Langley for analysis. The photographs contained some flaws from imperfections in the film processing system, and from unexpected technological problems that arose during the missions. Like on missions of exploration across eras, the Lunar Orbiter team members experienced moments of surprise and sometimes their technology did not always behave as planned. But for the most part the images were high quality and proved extremely useful in the Apollo planning process. The

[89] The Boeing Company, Lunar Orbiter III, p 19.

significance of this accomplishment for the scientists and Cold Warriors is hard to overstate—these photographs contained much of the environmental information they needed to find landing sites. For the scientists and engineers, the photographs represented not only a way to deliver on their promises to the warriors, but a significant step in the scientific exploration of the Moon. A 1963 paper on the future of photography found within Kodak historical materials may give us a sense of how the engineers and scientists felt about this sort of technology. The author wrote:

> "Most often, even in instrumentation applications, we want to 'see it,' and photography is essentially unique in being able to substitute for our eyes in obtaining this sophisticated information. Since the eye has sometimes been described physically as an extension of the brain, photography can certainly be described as an extension of the eye."[90]

The engineers at Kodak gave the warriors and the scientists the ability to bring their eyes closer to the lunar surface. It took a concerted team effort to transform what they saw into useful knowledge.

[90] "General Comments on the Future of Photographic Instrumentation," 1963, Kodak Historical Collection #003, D.319. Legacy, Rare Books, Special Collections, and Preservation, River Campus Libraries, University of Rochester.

Chapter 3: Flying the Moon

3.1 Lunar Reconnaissance

The first Lunar Orbiter mission started the same way as many other in the history of space exploration: with a launch delay. Problems with the Atlas rocket on August 9, 1966 led to a one day postponement. On August 10, a successful launch sent Lunar Orbiter I (LOI) on its way to the Moon. When flight operators turned on the navigation system the next day, they immediately ran into problems that put the entire mission in jeopardy. Spacecraft sensors failed to find Canopus, the reference star for celestial navigation, threatening the ability of the team to properly orient and control the spacecraft.[91] The team went into action to diagnose and fix the problem—they had anticipated the potential for this sort of event, and had systems to handle unexpected issues. The engineers knew the spacecraft inside and out and had the ability to react to problems with their vehicle.[92] The issues they confronted were sometimes the result of interactions between the many intricate components of the vehicle. They spacecraft and its structure can be seen in Figure 6 below.

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[91] Byers, pp 228-229.

[92] In a practice that seems somewhat unique to space exploration, one of the primary techniques involved using identical spacecraft back on Earth. These ground-based spacecraft were used to test theories about what went wrong, and to try possible solutions before sending commands to the spacecraft actively in orbit. Byers, pp 245-246.

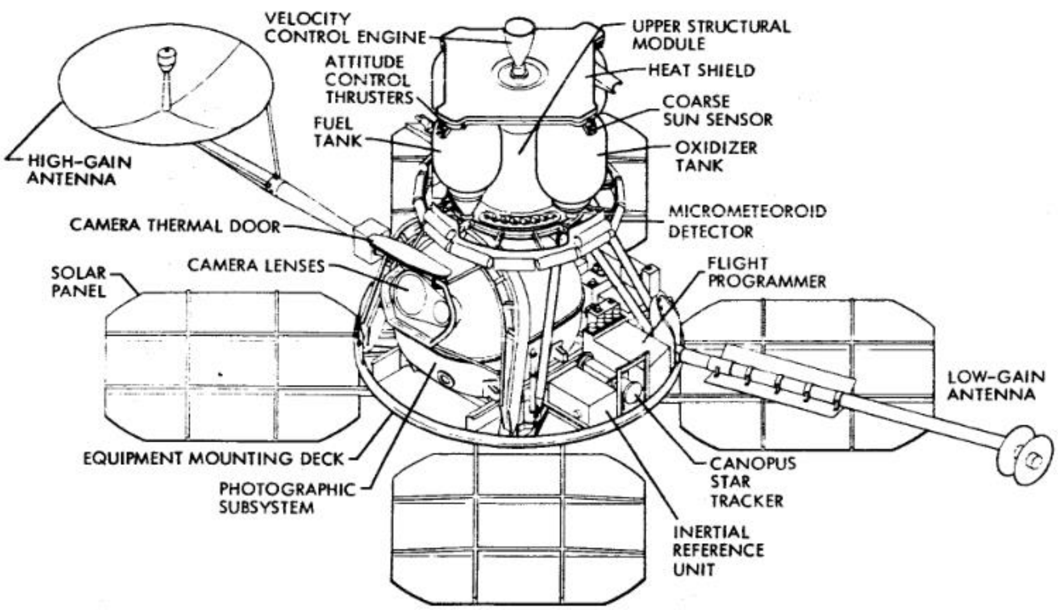

Figure 6: "Lunar Orbiter Spacecraft." From a NASA press release, showing a detailed view of spacecraft components.[93]

Planning for this sort of eventuality was an important part of the Lunar Orbiter project. Engineering and operations teams worked together to create contingency plans for response to specific problem scenarios. They were also cognizant of the fact that these would not cover every problem that might arise. [94] Based on a 1967 conversation with mission team members, NASA historian Bruce Byers described how the planners took this into consideration when designing both the spacecraft and mission operations:

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[93] National Aeronautics and Space Administration, "Lunar Orbiter Flight Set for August," News Release (66-195), 1966, p. 6-7

[94] Byers, pp 225-226.

> "NASA and Boeing had designed Lunar Orbiter to be 'tweaked.' It was not launched and sent on its way to the Moon and then left alone to perform its mission automatically and expire. On the contrary, it was designed to operate with the assistance of ground controllers to overcome risks in each mission, potential failures in subsystems, and the external hazards of space."[95]

In many historical missions of exploration, unexpected environmental conditions or technological failures were common unanticipated challenges, and it was no different in the first days of Lunar Orbiter I (LOI). The problems with the navigation systems were soon compounded by issues with heat management.

While operators monitored the spacecraft heat, they tried pointing the Canopus sensor at the Moon itself, helping them verify that the equipment was functioning correctly. They figured that the spacecraft structure was reflecting light in such a way that it confused the sensor. In response, operators changed the navigation procedures mid-flight to use the Canopus sensor only when the Sun was behind the Moon, or to use the Moon itself as reference during certain maneuvers. Flight operators then had to figure out a way to orient the spacecraft so that critical components faced away from the sun, while continuing to investigate the issues with the Canopus sensor. They sent reorientation commands every few hours, keeping temperatures in check and continuing to investigate the issues with navigation. Every little thrust used to change orientation during this diagnostic juggling meant a

[95] Byers, p 227.

slight acceleration of the spacecraft, adding to the potential problems that needed to be monitored. On August 14, operators managed to put LOI safely into orbit around the Moon.[96] But the bumpy ride to the Moon had consequences for the power systems and fuel reserves that operators would have to compensate for.[97] LOI sat in orbit for close to five days as flight controllers got a handle on the orbit they found themselves in, and waited for "proper target illumination."[98] The light on the lunar surface needed to be just right for successful execution of the mission proper.

The goal of the first three Lunar Orbiters was to find a site for the first Apollo landing. NASA offices with interests in Lunar Orbiter collaborated through numerous committees to plan the missions. They included outside counsel—the USGS and Bellcomm played an important role in both these planning sessions. Planners used USGS and Air Force maps of the Moon, made with telescopic observations and images from the Ranger spacecraft, to pick preliminary candidate sites. These were called Apollo "zones of interest" and were scheduled to be imaged in more detail by Lunar Orbiter. The committee planned at least four orbiters with the hope that by the end of the first three missions, they would get all the information they needed. If the warriors got the photographs they wanted, the

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[96] Byers, pp 229-233.
[97] Byers, pp 232-233, 239.
[98] The Boeing Company, Lunar Orbiter I, p 1.

scientists would get to take the wheel on any subsequent missions.[99] When the camera was tested for the first time, this prospect seemed very uncertain.

On August 18, 1966, operators took the first photographs of the Moon using Lunar Orbiter I. The pictures of Mare Smythii arrived on Earth just five hours after they were taken. This quick turnaround was not the standard procedure. During the first several Lunar Orbiter missions, most of the photographs were transmitted near the end of the mission. However, when they needed to, operators could receive images quite rapidly by processing and scanning a limited section of the film. In cases where they directly transmitted images in this way, Kodak engineers at ground stations saw images of the Moon with relatively little time-lag. Art Cosgrove was a Kodak engineer working at these ground stations and described in a *Kodakery Podcast* interview how he and his team members were able to get the first look at the lunar surface using two different methods. As the signals from Lunar Orbiter arrived, Cosgrove claimed that the engineers became so accustomed to what the signals represented that they were able to use the intensity of the signal to get a vague idea of the surface topography. They also rigged up an oscilloscope to become a monitor that turned the signals into rough and temporary images as they came

[99] Byers, pp 190-194.

in.[100] After they received these signals, it was the responsibility of these Kodak engineers to reconstruct the full images.

The first pictures received by the LOI team revealed yet more problems. The high-resolution photographs showed "smearing"—a blurring effect that indicated complications with the image motion compensation system. Testing revealed that this only occurred when the V/H sensors were active. Operators turned to Eastman Kodak technicians to figure out potential solutions. After further tests, they determined the cause: electromagnetic interference from the V/H sensor was disturbing the operation of the shutter on the 610mm lens. Kodak engineers recommended a lower orbit for later photographic passes, hoping that the V/H sensor would produce less electrical noise at lower altitudes. While there was a slight reduction in the "smearing" effect when they tried this technique, it was not significant enough to fully salvage high resolution photography from the first mission. Despite the issues, the Lunar Orbiter team members were still able to glean some information from the "smeared" pictures.[101] An example of this effect is seen in Fig. 7 below.

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[100] Art Cosgrove, (Art Cosgrove: Kodak and the Lunar Orbiter Mission), Interview with Meagan Ramplin and Joshua Coon. *The Kodakery*. Podcast Audio. February 03, 2016.
[101] Byers, pp 236-240; Boeing, Lunar Orbiter I, pp 1, 74-75.

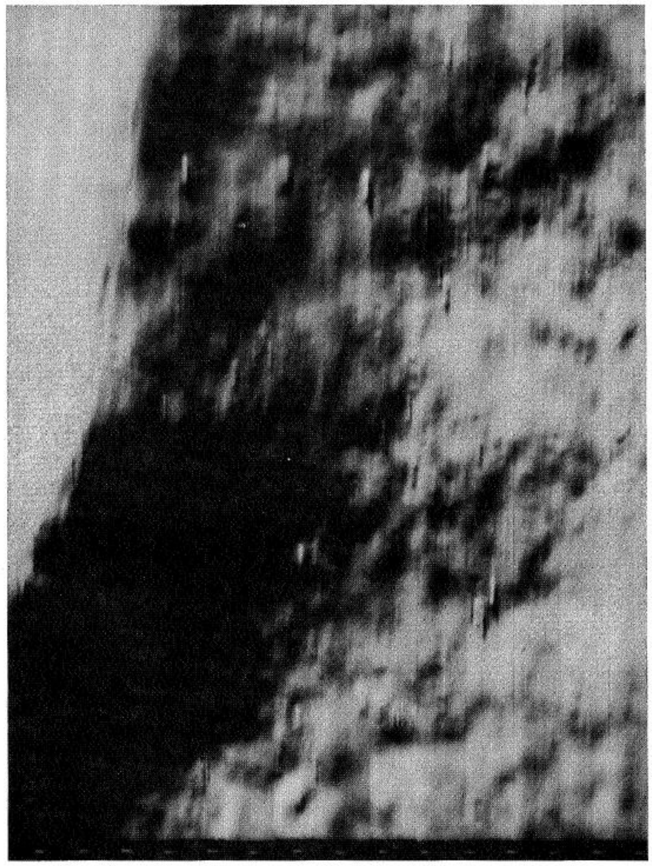

Figure 7: "Smear" on a Lunar Orbiter I photograph. Original caption reads "Detail in 610-mm Photograph Frame 85 Dionysius"[102]

For the most part, camera operation was planned and scheduled as precisely as possible, focused on Apollo zones of interest. However, in keeping with the ethos of flexibility adopted by mission planners, spacecraft operators had the ability to send new commands at will. When this happened, operator control over the spacecraft was quite direct—the Boeing contractor report to NASA for Lunar Orbiter

[102]The Boeing Company, Lunar Orbiter I, p 19.

I noted that "photography of unplanned specific targets required computation and spacecraft control essentially in real time since each target presented a unique problem."[103] In addition to providing better photographic results, this level of direct control also provided the mission team with the ability to take advantage of unexpected opportunities or compensate for hitches in the schedule.

On Lunar Orbiter I, an unplanned maneuver led to an important turning point in the overall mission, and a significant moment in space exploration history. Although it was not in the original plan, NASA officials wanted to use Lunar Orbiter to take a photograph of the Earth. This was a controversial concept for Boeing representatives, who feared that if anything went wrong on an unplanned maneuver, they might not receive full compensation for their contract. After reassurance from the NASA officials, Boeing approved. Operators pointed the spacecraft at the Earth, taking a photograph of the Moon's limb with the Earth rising above. It was the first time such a photograph had been taken from the Moon, and it foreshadowed the famous Earthrise photograph taken on Apollo 8. But the oblique view of the far side of the Moon also proved revelatory to the lunar scientists.[104] Boeing's contractor report noted that these photographs demonstrated "the value of

[103] The Boeing Company, Lunar Orbiter I, p 64.
[104] The Boeing Company, Lunar Orbiter I, p 33.

oblique photography for interpretation of lunar topography" and more oblique photos were planned for subsequent missions.

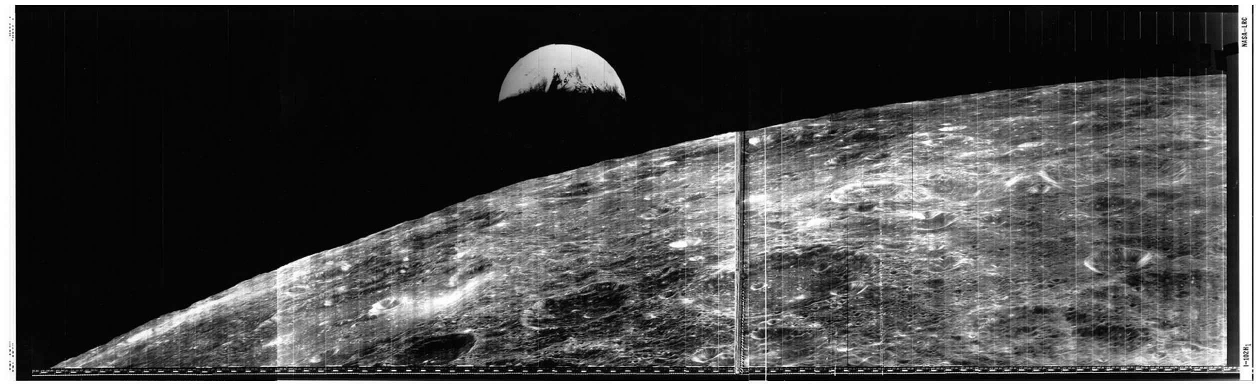

Figure 8: Lunar Orbiter I, Frame 102. The first image of the Earth from the Moon.[105]

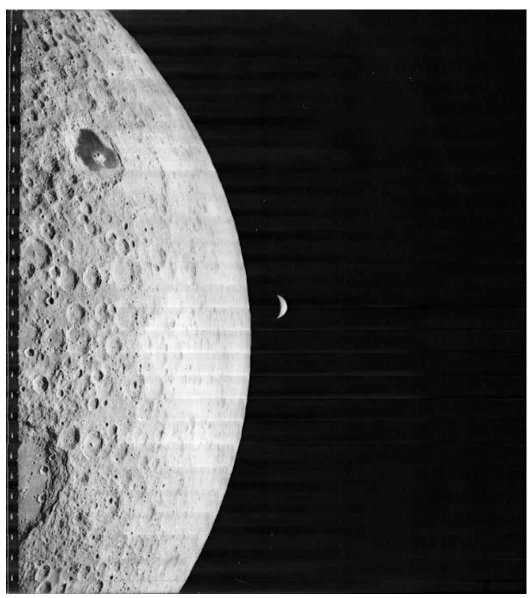

Figure 9: Lunar Orbiter I, frame 117.[106] *The second photograph taken of the Earth on Lunar Orbiter I, taken August 23, 1966.*[107]

[105] NASA, Lunar Orbiter I, Frame 102; H1, H2, H3. August 23, 1966. Photograph. NASA Space Science Data Coordinated Archive.

Science was able to sneak into the first mission in another significant way, with important implications for the history of exploration more generally. Prior to the Space Race, large portions of the far side of the Moon were obscured to every human in history. At the time of Lunar Orbiter I, the only knowledge about the far side of the Moon came from a handful of fuzzy images from Soviet lunar probes. The problems encountered during the first mission inadvertently led to the opportunity to take more images of this unknown landscape. Operators had designed camera tests to diagnose the shutter malfunction that involved taking pictures, and they decided to use some of these test frames to capture images of the far side. They also took some images of the lunar far side using film that had been "budgeted" for mechanical procedures when the cameras would not be over Apollo zones of interest. By the end of the mission, operators had taken eleven images of the far side of the Moon.[108] These opportunistic photographs provided high resolution views of completely unseen territory. The effort to learn more about the far side would continue later missions.

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[106] NASA/Lunar and Planetary Institute. *Frame 1117*, med. Lunar and Planetary Institute.; The images from the Lunar and Planetary Institute (LPI) have had a small amount of additional processing applied. They are newer scans, and LPI took steps to keep all photographs oriented in the same direction, to reduce banding in the images, and to enhance contrast.

[107] The Boeing Company, Lunar Orbiter I, p 33.

[108] The Boeing Company, Lunar Orbiter I, p 64.

Lunar Orbiter II launched relatively quickly after Lunar Orbiter I, but engineers made some changes to the spacecraft based on the experiences in the first mission. They painted parts of the antenna and the solar panels black, to reduce the reflections that confused the Canopus sensor. The issues with the V/H sensor were resolved, and engineers made other minor adjustments to the film mechanisms. They also added a thermal paint to the equipment deck to make heat management easier.[109] Air Force mapmakers analyzing the film from Lunar Orbiter I also noticed that the reconstruction process was not always perfect, adding minor distortions that made mapping more difficult. Duane Lyon, an Air Force photogrammetrist, suggested adding a reseau to the film—pre-exposed marks that could be used to assist reconstruction.[110]

Lunar Orbiter II launched in November 1966. The mission was designed to obtain more detailed photography of the most promising Apollo zones of interest. One major goal was to test theories that scientists had developed about the topography of rays that extended from certain craters. They targeted the area between the craters Copernicus and Kepler in particular, hoping to determine its suitability as a landing site. After 33 orbits around the Moon, the operators began the

[109] Byers, pp 251-258.
[110] Kopal and Carder, p 126.

photographic mission.[111] Overall, Lunar Orbiter II was smooth and productive, in part thanks to the learning experience of the previous mission. Although pre-planned photography dominated the mission, there were still important instances where the orbiter team members were able to improvise. One of the most significant involved once again taking advantage of problems with the spacecraft.

One of the issues that the orbiter team had been dealing with involved Kodak's Bimat film. The Bimat tended to stick to the film if too much time elapsed between frames. To prevent the sticking, sometimes the film and Bimat were moved by taking a photograph. The hope was that these frames could still be taken over Apollo zones of interest, but Douglas Lloyd at Bellcomm suggested taking a highly oblique picture of the crater Copernicus as Lunar Orbiter II made a low pass. NASA officials resisted at first, but persistence paid off and Lloyd eventually convinced them to take the shot.[112]

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[111] Byers, pp 255-256.
[112] Byers, pp 255-256.

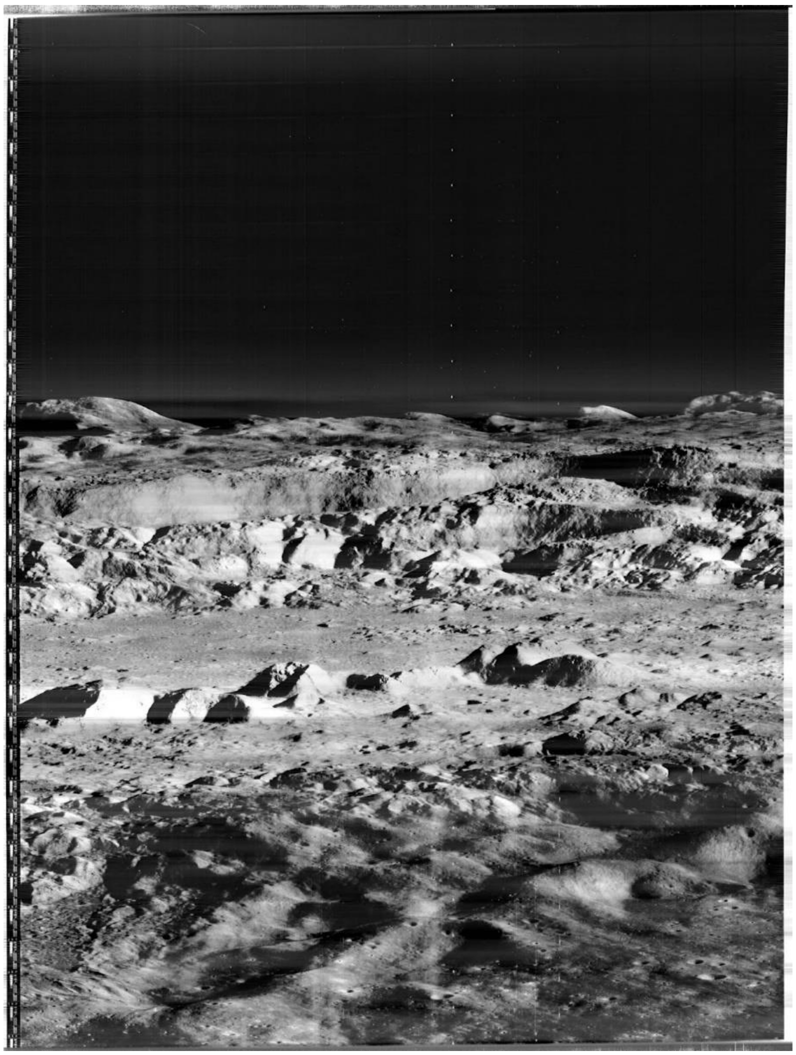

Figure 10: Lunar Orbiter II, frame 162.[113] This photograph shows the crater Copernicus at a highly oblique angle.

Byers described in detail how this photograph of Copernicus, along with other oblique photographs, wound up being some of the most significant of the early orbiter missions:

[113] NASA/Lunar and Planetary Institute. *Frame 2162, H3*. Photograph. Lunar and Planetary Institute. https://www.lpi.usra.edu/resources/lunarorbiter/frame/?2162

> "This and oblique pictures of the Marius Hills and Reinger Gamma proved to be extremely valuable to the photogrammetrists, astrogeologists, and other scientists connected with the Lunar Orbiter and Apollo programs. The nation's news media described the Copernicus pictures as 'one of the great pictures of the century.'"[114]

People had never seen the Moon in quite this way before. The Copernicus picture almost gives the impression of what you might see looking out the window of an airplane that's about to land. The photograph appeared in scientific journals, along with other oblique photographs. It was the star turn in a very successful mission. Because of the success of Lunar Orbiter II, Lunar Orbiter III's mission would be mainly focused on obtaining more photography of the best candidate sites already identified, rather than searching for new sites.

This was a good thing for the Apollo mission, because Lunar Orbiter III experienced the worst of the failures experienced during the project. The troubles nearly began on February 13, 1967, when a solar flare struck, but luckily no damage to the film occurred. Photography started on the 15th and went fairly well until the film advance mechanisms began experiencing trouble. Officials initiated the read out early, but the mechanism failed and led to the loss of 72 frames out of 211. This did not affect the Apollo mission too drastically, but may have been a disappointment

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[114] Byers, p 257.

for scientists, who had been given more input on the third mission.[115] For now, the scientists would have to make do until the launch of Lunar Orbiter IV and V. In the meantime, they had an important job to perform for the Cold Warriors.

3.2 The Science of Site Selection

In studying the Moon, increasing resolution was an essential element of discovery and planning. As the resolution of telescopes improved and the first robotic probes successfully sent images back to Earth, increased resolving power meant more detail could be discerned. For instance, Eugene Shoemaker noted that resolution played an important role in studying craters with diameters less than a kilometer.[116] Details like these played an important role in developing a better understanding of the lunar surface as a whole—an important part of developing the broadly applicable understanding of lunar natural history that was so important to the Apollo mission. Both the top-down and oblique images became important to understanding the lunar topography and preparing for the first landing. The

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[115] Byers, pp. 259-266.

[116] Eugene M. Shoemaker, "Preliminary Analysis of the Fine Structure of the Lunar Surface in Mare Cognitum" in *The Nature of the Lunar Surface: Proceedings of the 1965 IAU-NASA Symposium*, ed. Wilmot N. Hess, Donald H. Menzel, and John A. O'Keefe (Baltimore: The Johns Hopkins Press, 1966), p 53.

combination of LOI, LOII, and LOIII photography gave the Apollo site selection teams enough information to do their jobs.[117]

The Lunar Orbiter photographs entered the scientific conversation almost immediately. In September 1966, after the first two Lunar Orbiters had launched, the American Astronautical Society held a symposium in which scientists presented papers and held a discussion about the larger issues involved in lunar exploration. The papers presented still relied far more on Ranger and Surveyor, but Nicholas M. Short of the University of Houston used his presentation as an opportunity to discuss how Lunar Orbiter photographs figured into the broader investigation of the Moon. He largely discussed how Earth analogues might be applied to understanding impact processes on the lunar surface. On one hand, the Orbiter photographs were helpful to him: "Certainly the Lunar Orbiter II view into Copernicus revealed precisely what I would expect to see in a 'younger' impact crater."[118] But at the same time, he made sure to describe in detail the limitations of these sorts of view for his work, saying that "the Ranger, Surveyor and Lunar Orbiter photos in themselves cannot provide direct, unequivocal evidence of shock effects…that would allow us to infer that impact occurred at or near the viewed

[117] Samuel C. Phillips, "Minutes of the Apollo Site Selection Board Meeting, March 30, 1967" (United States Government Memorandum, June 1967), p 5.
[118] Nicholas M. Short, "A Review of Shock Processes Pertinent to Fragmentation and Lithification of the Lunar Terrain" in *The Interpretation of Lunar Probe Data*, ed. Jack Green (Washington, D.C.: American Astronautical Society, 1967), p 57.

surface." But other scientists found the photographs more useful, especially when it came to the scientific investigations more relevant to Apollo site selection.

In 1967, Alan L. Filice of the Jet Propulsion Laboratory published results of his research that attempted to resolve some of the disputes about the composition of the lunar surface and its ability to support a lander. He used frame H-76 from Lunar Orbiter II to analyze the track created by a rolling boulder in the crater "Sabine D" within the Sea of Tranquility. Filice used the photograph to identify the size of the boulder (13 meters wide), the width of the track (6 meters), and was able to infer the static-bearing strength of the lunar surface in that area. He compared his findings to data from studies of Ranger and Surveyor data to suggest subtle alterations to their understanding of how much weight the surface could hold. He was investigating this particular location for a reason, writing that "a measurement in western Mare Tranquillitatis is important because this area is a potential landing site for both Surveyor and Apollo missions to the Moon."[119] This comment and Filice's result take on some unexpected significance in retrospect—Apollo 11 would eventually land in the western Sea of Tranquility, not far from Sabine D, which the IAU later renamed "Collins" after Apollo 11 astronaut Michael Collins.

[119] Alan L. Filice, "Lunar Surface Strength Estimate from Orbiter II Photograph" *Science* 156 (1967): 1486-1487.

The technique that Filice used was referred to by the Apollo site selection Committee as the use of "natural penetrometers."[120] Scientific studies like these were highly important to their analysis and assessment of landing sites. Scientists were able to combine information extrapolated from Orbiter photography with data from Surveyor to arrive at conclusions about the surface material. Orbiter photographs provided them highly detailed information about topography and geologic features.[121] The members of the Apollo Site Selection Committee carefully began to use this information to narrow down potential landing sites and to prepare the astronauts.

As early as 1966, the site selection committee discussed the need for new large-scale maps that could be used for training.[122] By 1968, new maps were being created that used Lunar Orbiter photographs combined with photographs taken by Apollo 8 and Apollo 10. The Air Force produced the Lunar Planning Chart Series (LOC) maps by creating mosaics of these photographs and plotting them against control systems they had developed using earlier telescopic mapping. For maps like this, non-existent lighting conditions were imposed so that every part of the map was apparently lit in the same way from the east. Airbrush was the primary method

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[120] Samuel C. Phillips, "Minutes of the Apollo Site Selection Board Meeting of December 15, 1967" (United States Government Memorandum, January 1967), p 1.
[121] Samuel C. Phillips, "Minutes of the Apollo Site Selection Board Meeting, December 15, 1966" (United States Government Memorandum, March 1967), p 1.
[122] Phillips, December 1966, p 4.

used to create this portrayal, and lithographs of the maps were limited to three colors: black, blue, and brown.[123] Maps and photographs were used to train the Apollo astronauts to recognize landmarks from above.

In March 1967, there were 11 "Lunar Orbiter target areas" that contained candidate sites.[124] These were evaluated based on several metrics, including the time of year when lighting would be best for a landing at each site.[125] Another crucial metric that led to the selection of these sites was the number craters and of potential obstacles in the "landing ellipse" at each site, determined through photogrammetric techniques. In March 1968, the selection committee was trying to narrow down the sites to just three. They designated the sites by the Lunar Orbiter II target areas in which they were contained—the eventual Apollo 11 site was contained in "II-P-6," for example. The closer they got a launch, the less that data from Lunar Orbiter was relevant in site selection, and the more the committee had to consider landing sites based on lighting at the projected landing time, capabilities of the landing module, and training of the first crews. In 1969, as it became clear that Apollo 11 would likely

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[123] Defense Mapping Agency Aerospace Center (DMAAC), *Lunar Cartographic Dossier*, ed. Lawrence A Schimerman (St. Louis: DMAAC, 1973), Section 4.1.1, p 1; Kopal and Carder, pp 132-133.
[124] Samuel C. Phillips, "Minutes of the Apollo Site Selection Board Meeting, March 30, 1967" (United States Government Memorandum, June 1967), p 3.
[125] Phillips, March 1967, p 2.

launch in July, August, or September the list of candidate sites was narrowed down to three, and the designations changed to sites 2, 3, and 5.

An annotated photograph in the July 1969 selection committee documents (Fig. 10) showed the landing ellipse for Site 2, which would become the landing site for Apollo 11 on July 20. The ellipse was superimposed on Lunar Orbiter photographs, a final testament to the success of the project. Farouk El-Baz used photographs and maps like these to train astronauts to recognize landmarks on their way to the landing sites.[126] Like Lewis and Clark, Armstrong and Aldrin had a decent idea of where they were going thanks to the scouting reports from above. But like their nineteenth-century counterparts, the scouting reports could not be perfectly detailed. As he piloted the lunar lander toward the surface, Neil Armstrong had to veer away from the intended landing site to avoid a field of boulders. The full nature of the landscape he finally set foot in was obscured even from the eyes of the Lunar Orbiter team by distance.

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[126] El-Baz, Oral History, pp 10-12.

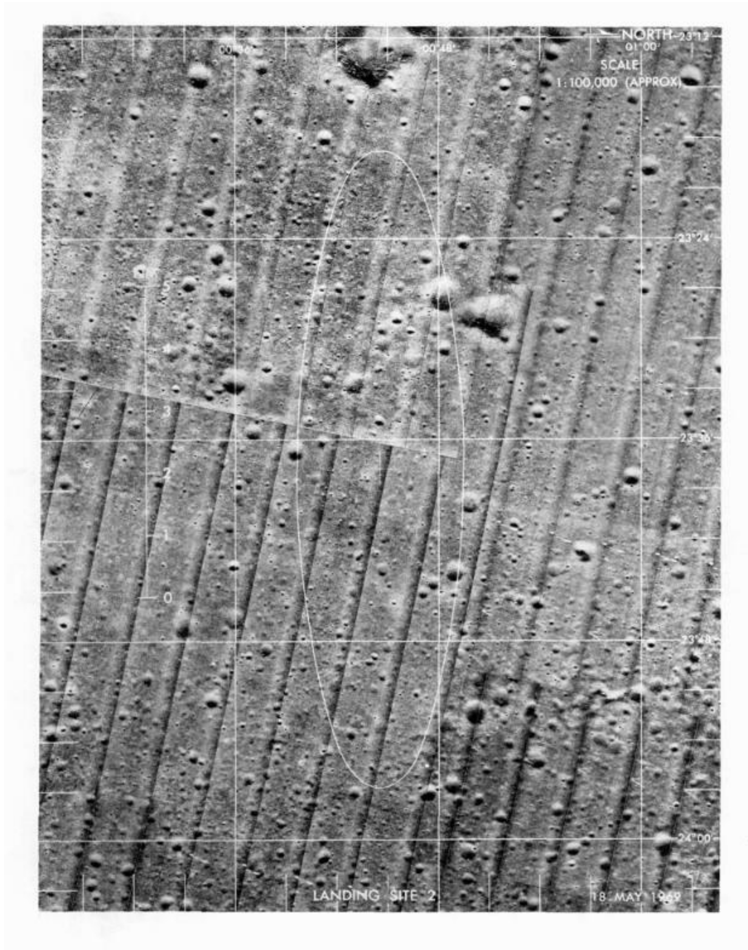

Figure 11: Photographic map of the Apollo 11 landing site. From a document in the minutes of the Apollo Site Selection Board meeting on July 10, 1969.[127] *The image is dated 18 May 1969 in the bottom right corner and titled "Landing Site 2." The final Apollo 11 landing site was around the upper left edge of the ellipse, slightly below the line marked 23 degrees, 24 minutes.*

Prior to the Lunar Orbiter and Apollo missions, administrators, engineers, and scientists worked together to set priorities. They defined mission constraints and

[127] Farouk El-Baz, "Recommended Lunar Exploration Sites (Apollo II through Apollo 20): Presented to the Apollo Site Selection Board July 10, 1969" in "Minutes of the Apollo Site Selection Board Meeting" (NASA Document, July 1969) https://www.lpi.usra.edu/lunar/documents/apollo-site-selection/Jul-10-1969.pdf

put together a plan. During the mission, engineers monitored the spacecraft closely, gave direct commands, and updated pre-planned instructions. During and after the missions, scientists spent a great deal of time with photographs and data, analyzing and discussing what they learned with others. The essential activities of planning, monitoring, overriding pre-set procedures with instantaneous commands, and later analyzing data seem consistent with a sketch of almost any mission of scientific exploration throughout history—the details of each molded by the technology available in their time. This process would continue with even greater emphasis on scientific discovery through Lunar Orbiter IV and V, and Apollo 12 through 17. NASA was true to their word, and the scientists got to take the helm after the primary mission was complete. But the scientists never truly got what they had hoped for.

3.3 Lunar Orbiter and the Scientist-Explorer

Lunar Orbiter was a microcosm showing the general relationship between the warriors and the scientists during the Cold War. Once the warriors had gained the reconnaissance information they needed, they gave control over to the scientists. It was a pattern that was followed by the Apollo program itself, and one could argue that a larger pattern of this sort played out over the broader history of the space program. During the Lunar Orbiter missions, as scientists received the first photographs and analyzed them, they were contemplating the future of their field. They carefully considered their role in the process of exploring the Moon and tried to sketch out a plan of how they wanted to proceed. Their conversations can give us an insight into how these scientists perceived their work on Lunar Orbiter photographs, and luckily, we have a wealth of documented discussions from space scientists in these crucial years.

The Iowa Summer Study and *Icarus* were just two of many attempts to organize the efforts of planetary scientists and space engineers during the early space age. These scientists and engineers held regular conferences and symposiums to share knowledge. It was thought to be important to widely publish the proceedings of these meetings, so that the current state of knowledge about the lunar surface would become more widely known. The organizers wanted to encourage others in the scientific community to share their theories. Knowledge was expanding rapidly, and leading scientists feared that "physicists, chemists, geologists, astronomers, and mathematicians who could contribute to our understanding of the surface of the moon are inhibited by the feeling that their remarks might either be contradicted by facts well known to other or might be so obvious as to appear trivial."[128] Through these published presentations and

[128] Wilmot N. Hess, Donald H. Menzel, and John A. O'Keefe, "Introduction" in *The Nature of the Lunar Surface: Proceedings of the 1965 IAU-NASA Symposium*, ed. Wilmot N.

conversations from these meetings, we get a glimpse into the evolving state of knowledge about the Moon resulting from missions of exploration, and how this knowledge played a role in the planning of further exploration. We gain insight into the motivations of scientists, and how they viewed their role in the larger history of exploration. We also get a sense of the political and economic context in which these discussions occurred, which can allow us to discover if the exploratory endeavor possessed some of the same types of motivations as previous episodes.

What were the priorities of space scientists that may have run contrary to NASA priorities? In the early stages of American space exploration efforts, scientists had a ravenous appetite for data. In a panel discussion on how to best utilize lunar probe data, Raymond McFee of JPL remarked on "the tendency to assume that, if we get as much data as possible, eventually somebody is going to find some use for them."[129] He warned of the potential for this to become unsustainable in the face of limited budgets, and suggested that a more focused approach of testing specific hypotheses would be warranted in the future. This seems to be exactly the trend we see later in the twentieth century, especially in the MER program. Those early stages of broad-based investigation feel like an echo of the Humboldtian broad-based

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Hess, Donald H. Menzel, and John A. O'Keefe (Baltimore: The Johns Hopkins Press, 1966), p, vii.

[129] American Astronautical Society, "Panel Discussion – The Impact of Lunar Probe Data on Future Space Missions" in *The Interpretation of Lunar Probe Data*, ed. Jack Green (Washington, D.C.: American Astronautical Society, 1967), p. 135.

scientific exploration of the nineteenth century. However, over time the geopolitical circumstances changed, and budgets for space exploration became more restricted. This combined with the difficulties and constraints particular to space exploration encouraged a trend towards finely honed and planned space missions, which still attempted to bring in as many disciplines as possible, within reasonable limits.

This more focused approach was also emphasized by the chair of the panel discussion, J.B. Edson of NASA. Edson seemed to believe that a focused hypothesis-oriented type of science was easier to justify to the broader public, because results could be shown that would justify the cost. But Gerard Kuiper pushed back against this idea, arguing that broad-based data collection was also of scientific value, as well as being valuable in terms of international prestige.[130] This discussion demonstrates that the priorities of the space program were still very much in flux, subject to the sometimes-conflicting interests of different scientific disciplines and philosophies, and often filtered through a political lens.

At this stage in the space program, the potential of direct economic benefit from lunar exploration was still very much in the discussion. The 1966 panel included Clifford Schultz of the U.S. Bureau of Mines, who described his view of the proper relationship between economic motivations and scientific investigation at

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[130] American Astronautical Society, pp. 138-143.

that stage of exploration. He expressed a belief that while resource utilization was an important aspect of lunar investigation, it should not be the guiding priority. In fact, he believed that the broad-based scientific investigations were already proving important to his work. Their efforts to develop mining systems had at first emphasized hard rock, but increasingly took into account soil mechanics because "these lunar probes continually narrow our concept of the nature of the lunar surface."[131] "If you're in the mining business, " Shultz elaborated, "you drill one core, it's pretty inconclusive…I would personally rather see a broad survey of the lunar surface."[132] Surveys like those conducted by Lunar Orbiter were being actively considered as having potential economic value, in addition to their scientific and political value. I think of Humboldt's broad survey for the King of Spain, and Lewis and Clark's broad-based inquiry at the behest of Jefferson. The differences between these episodes seems to be primarily the degree of emphasis placed on the economic results. For Lewis and Clark, economic usefulness was the raison-d'etre. For Humboldt, it was a means of securing passage for his own scientific project, and of value primarily to Spain. For the U.S. space program, it was an outside possibility worth investigating.

[131] American Astronautical Society, p 144.
[132] American Astronautical Society, p 145.

Likewise, some form of settlement was also involved in this discussion, even if it was for temporary science stations. Edson discussed the implications of Orbiter and Surveyor data for the construction of inhabitable buildings out of lunar material, and even the paving of roads.[133] But in the short-term, the primary object of the U.S. space program was simply getting people on the surface of the Moon. As J. Burridge of the Apollo program put it: "The Apollo Program, as identified and initiated by President Kennedy, kind of comes to a halt when the objective of landing astronauts on the lunar surface is met. The next question is exploration of the lunar surface…I don't really think we are faced with the question 'will we explore the Moon?' I think we are faced with the question of how we are going to explore it and at what rate."[134] The conversation quickly strayed towards the answer to this question, and it became clear how the scientists and engineers in the room conceptualized the type of endeavor these robotic probes were a part of.

The primary point of debate became the relative merits of robotic probes, non-scientist astronauts, and scientist-astronauts. This involved weighing what types of experiments each type of exploration could perform, the extent to which sample return was possible, and the quality of the science performed by each. Kuiper made it clear that this was part of a debate that had been ongoing since at

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[133] American Astronautical Society, pp 146-147.
[134] American Astronautical Society, pp 149-150.

least four years earlier at the Iowa Summer Study. One possibility that was floated was non-scientist astronauts being guided in real time by scientists through TV/radio equipment, effectively turning the astronaut into a tool for remote sensing. Kuiper and representatives of NASA then debated the expense issues involved in crewed vs uncrewed programs, the relative priority of finding a safe landing location for the first Apollo surface mission, and the scientific priorities that Kuiper believed were taking a back seat. Then Daniel Hale of the Marshal Spaceflight Center spoke up with a short speech that was immediately acknowledged as capturing the spirit of the room (although not being very helpful to the discussion).

Hale directly tied the conversation to perceived historical precedents and the lessons that the space program could possibly learn from them: "Do you think that Darwin could have realized as much from the voyage of the Beagle, if he had not seen the world, made the collections, pressed his own plants, and brought them back to England, rather than 3 years later do the analyzing and classify of the data obtained by others? Most of the things that Darwin got from that voyage were probably serendipitous; he didn't anticipate them!" Hale then invoked Magellan as well as Lewis and Clark to point out the long-term benefits that can result from in-person, expensive, and risky missions of exploration. Kuiper remarked that the example of Darwin had also been brought up in Iowa, as the scientists speculated over the "effectiveness of Darwin over the average traveler."[135] These scientists clearly thought of themselves as operating in roughly the same tradition as nineteenth century scientific exploration.

Amongst this group, there was no doubt that robotic probes played an important part of this work, but there was significant doubt that they were sufficient to obtain the type of results desired by the scientists and engineers. But due to the unique political, environmental, and technological challenges of space exploration, subsequent scientist-explorers would have to make it work. A remark made by Edson at the conclusion of the 1966 session reinforced why: "For logistic support, Darwin was supported by about five thousand years of maritime history. The poor guy who stands on the surface of the moon for the first time won't be in quite that fortunate a position."[136] For the time being, these scientists needed to use what they had. And what they had was Ranger, Surveyor, and Lunar Orbiter.

3.4 Urey's Birds - Scientific Exploration Through Photography

In a 1965 paper analyzing Ranger photographs, Harold C. Urey recounted flying over the mountains of Arizona and noticing features in the desert that reminded him of a "lake" seen near a crater wall on the Moon. His experience

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[135] American Astronautical Society, p 161.
[136] American Astronautical Society, p 161.

reinforces for us the extent to which scientists were extending the techniques of aerial photographic analysis from the Earth to the Moon, and Urey even made a strong claim about the way people interacted with aerial photographs. "Sometimes I think people are rather like birds—birds that are born with a map of the sky in their brains that enables them to fly from one part of the world to another."[137] Other scientists used aerial photographs in their analysis of lunar photographs. They presented Ranger images alongside photographs of snow-covered depressions in Indiana or cratered volcanic ash in Hawaii.[138] Their papers often included a combination of telescopic images of the Moon, aerial photography of the Earth, and photographs from lunar robots. Some scientists also included images produced through laboratory testing.[139] This type of analysis and information sharing continued with Lunar Orbiter images, many of which used the same types of vantage points as terrestrial aerial photographs and were analyzed in the same fashion. Through Lunar Orbiter IV and V, scientists got access to truly comprehensive orbital images outside of the Apollo, allowing them to extend their scientific eye more broadly across the surface of the Moon.

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[137] Urey, p 20.
[138] E.A. Whitaker, "The Surface of the Moon" in *The Nature of the Lunar Surface: Proceedings of the 1965 IAU-NASA Symposium*, ed. Wilmot N. Hess, Donald H. Menzel, and John A. O'Keefe (Baltimore: The Johns Hopkins Press, 1966), pp 92, 97, 98.
[139] Gault, Quaide, and Oberbeck, pp 125-131.

Whereas the first three missions had remained in largely equatorial orbits of interest for Apollo, Orbiters VI and V were placed in polar orbits around the Moon. Polar orbits meant that over the course of these missions, nearly all of the lunar surface would pass under the Orbiter camera lenses. This included the lunar far side and much of the polar regions that remained unexplored. On May 4, 1967 crews launched Lunar Orbiter IV. On its way through the Van Allen Belt—one of the first environmental hazards encountered by explorers leaving Earth—the spacecraft was hit with a much higher dose of radiation than the others. But engineers had adequately protected the film storage, and no damage occurred to the film. Lunar Orbiter IV teams then had to contend with another type of environmental problem: managing the internal environment of the equipment. Spacecraft designers had included a door covering the camera enclosure to manage the heat and humidity of the internal environment. But midway through Lunar Orbiter IV's mission, the door failed to close. Operators tried several techniques over the course of the mission to prevent light leaking onto the film and condensation from forming on the lenses. The solution they arrived at was to partially close the door, while carefully orienting the spacecraft with respect to the sun so that the problems were minimized. This strategy was quite successful, although some of the photographs from Lunar Orbiter IV suffered from fogging, reducing the contrast to varying degrees.[140]

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[140] Byers, pp 273-278.

Operators also received closer to real-time views of the lunar surface, because of an operational change that was made in reaction to the mechanical problems on Lunar Orbiter III. Rather than waiting until the end of the mission to read out photographs, operators read them out as they were processed, in case the film mechanisms failed again.[141] Despite the fogging issue, the team was able to use Lunar Orbiter IV to photograph geologically significant areas of the polar regions and obtained more photographs of the far side. At the end of the photographic mission, they placed Lunar Orbiter IV into the planned orbit for Lunar Orbiter V, and they were able to use the spacecraft to scout out the gravitational conditions in that orbit.[142]

Flight controllers placed Lunar Orbiter V into orbit around the Moon on August 5, almost a year after the launch of the first mission. Through input by USGS representatives such as Donald Wilhelms, the fifth mission's list of targets included numerous sites of purely scientific interest. Of the 212 frames in the plan, only 44 were given over to Apollo.[143] Almost two dozen unseen areas on the far side were captured on film.[144]

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[141] Byers, p 270.
[142] Byers, p 283.
[143] Byers, pp 288-289.
[144] Byers, p 296.

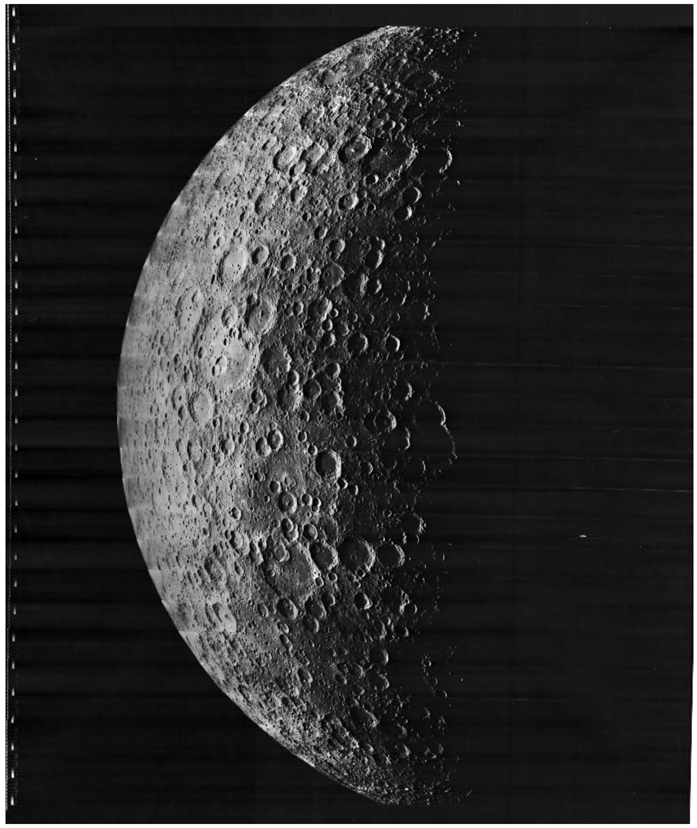

Figure 12: Lunar Orbiter V's view of the lunar polar regions and large parts of the far side.[145] *Some of these areas had never been seen before.*[146] *The Moon's north pole is toward the top of the image, close to the cluster of large overlapping craters near the terminator.*

The mission team also took another unplanned photograph of the Earth, once again using a frame budgeted for managing the Bimat. They used the 610mm lens, revealing some detail of the continents.[147]

[145] NASA/Lunar and Planetary Institute. *Frame 5008, med*. Photograph. Lunar and Planetary Institute. https://www.lpi.usra.edu/resources/lunarorbiter/frame/?5008
[146] Byers, pp 293-294.
[147] Byers, pp 294-295.

Figure 13: The Earth from Lunar Orbiter V.[148]

The images from all the Lunar Orbiters were a bounty for scientists, allowing them to truly transform the Moon into a destination for field science. At first, scientific papers and presentations of the lunar surface treated it very much as a scientific object. Features were isolated and analyzed. Conclusions were put together into larger theories, and the result was a big-picture understanding of the Moon that put specific locations into context. This told a story of the Moon's geological history

[148] NASA/Lunar and Planetary Institute. *Frame 5027, h2*. Photograph. Lunar and Planetary Institute. https://www.lpi.usra.edu/resources/lunarorbiter/frame/?5027

that allowed scientists to construct the Moon as a place, and specific sites on the Moon as potential landing areas for scientifically oriented Apollo missions. Farouk El-Baz played an important role in putting this puzzle together, synthesizing scientific work on Lunar Orbiter photography and using it to suggest sites for later Apollo missions that could be more focused on scientific exploration.

In an oral history in the NASA history collection, El-Baz discussed being hired by Bellcomm as a geologist and getting pulled into lunar geological analysis by the gravity of the project. He was invited to a meeting at NASA's Langley Research Center by NASA geologist Donald Beattie, which was mostly attended by geologists from the USGS based in Flagstaff, Arizona. This was his first direct exposure to the geological work being done in connection with Lunar Orbiter. Afterward he went to NASA headquarters, where he got access to the Lunar Orbiter pictures, and spent three days organizing the photographs and studying them. He continued to attend the geological meetings at Langley and claimed to have noticed a major deficit in the USGS analysis. The geologists were focused too much on individual sites, El-Baz said, rather than trying to understand the "different types of features and their distribution." To his mind, these larger patterns would be important if scientists wanted to fully utilize a limited number of Apollo missions for scientific purposes.

He put together a list of sixteen sites on the lunar surface that represented areas with different types of rocks and surface features.[149]

Later in 1968, El-Baz compiled an analysis of sites that were geologically interesting to the Group for Lunar Exploration Planning (GLEP), an advisory group for the Manned Spacecraft Center.[150] The report listed nine sites that the group recommended for later Apollo landings, and detailed the types of activities or experiments that astronauts might conduct at those locations. Each of the descriptions was accompanied by frames from Lunar Orbiters IV or V, along with relevant sections of one of the lunar charts produced by the Air Force. They made these recommendations with the understanding that the first three Apollo landing missions would be visiting mare and the Fra Mauro formation. [151] The Fra Mauro mission was pushed to Apollo 14 after Apollo 13 was forced to abort its mission. Of the three remaining Apollo landings, two of them touched down in areas recommended by GLEP. Apollo 15 astronauts visited Rima Hadley, which was GLEP site number 5. The Apollo 17 crew landed in the Littrow area, which was GLEP site number 2. One of the members of Apollo 17 was Harrison Schmitt, a geologist and

[149] El-Baz, Oral History, p 2-3.
[150] Farouk El-Baz, "Geologic Characteristics of the Nine Lunar Landing Mission Sites Recommended by the Group for Lunar Exploration Planning" (NASA CR-95403, Office of Manned Space Flight, May 31, 1968).
[151] El-Baz, Geologic Characteristics, p vi.

member of the GLEP site selection team.[152] This represented a significant moment for the scientific community, who had been grappling with the limitations of orbital photography.

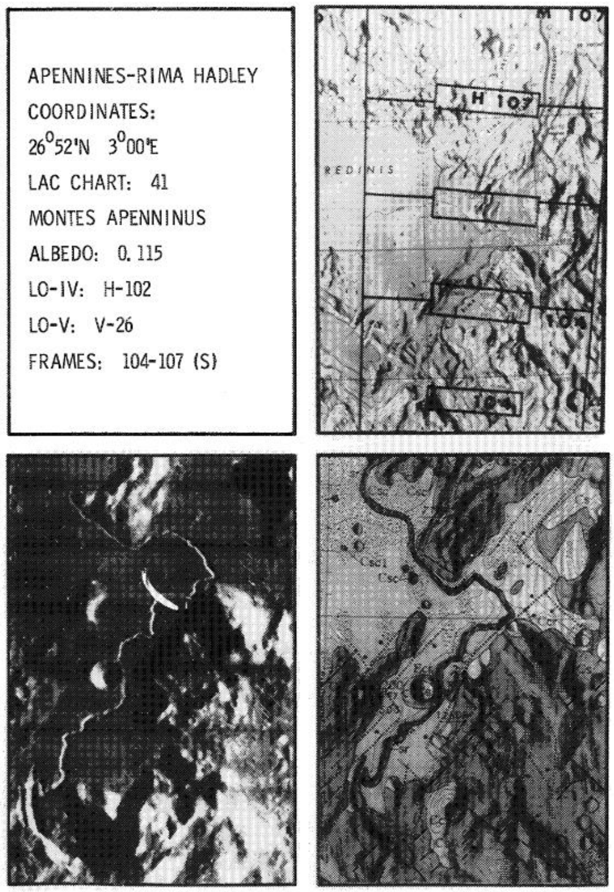

Figure 14: A collection of images from El-Baz's report on GLEP selection committee recommendations. This area would become the landing site for Apollo 15.[153]

[152] El-Baz, Geologic Characteristics, pp vi, 4.
[153] El-Baz, Geologic Characteristics, p 25.

Many of the claims about the Moon based on remote sensing images were necessarily speculative. This was especially true prior to Surveyor and Apollo. Missions before Lunar Orbiter had returned some images, and scientists attempted to work with them as much as possible. In 1965, about a year before the first Lunar Orbiter mission, H.C. Urey pointed out the difficulty. In his analysis of Ranger photographs, he pointed out that "we can make many suggestions about the moon, but we have rather great difficulty in proving that what we say is more than just possibilities."[154] This fact remains a problem for remote sensing more broadly.

Speculation based on limited information has been an integral part of scientific exploration for most of its history. The mapped lines of magnetic deviation from Edmund Halley's expedition had to be mathematically smoothed to become legible. Illustrations of creatures extracted from the deep sea by the HMS *Challenger* scientists were not representations of what sat on the illustrators table, but what they imagined the creatures looked like in their natural environment. This type of speculation is a part of the scientific process, because it provides a testable hypothesis. These speculations provide essential guidance for expeditions that come later. The orbital images gave the explorers a position at the top of the hill. But what they could learn was limited – they were really looking for the best places to conduct their fieldwork.

[154] Urey, p 20.

Vertesi reports that some of the scientists who worked on the later MER missions referred to the type of scientific work done with Lunar Orbiter images as "lookiloo" science. Scientific work done with orbital imagery—and visual imagery in general—was not enough for them. They contrasted these practices with the work done through rovers on the ground, or through non-photographic instruments that provide concrete data beyond the merely visual. This was due to the perceived importance of "ground-truthing," the process of verifying suppositions based on remote sensing images using direct investigations on the ground.[155] But the scientists involved in Lunar Orbiter also believed that ground-truthing was essential. Many also believed that the only way to be sufficiently confident in ground-truthing was to send humans to the surface of the Moon and the planets. Through Apollo, lunar science got its in-person ground truthing. But for many of the scientists, this might as well have been a form of remote sensing through pre-programmed human operators. Only one Darwin, one scientist-explorer, was ever sent to the surface of the Moon in the person of Harrison Schmitt.

Even without the direct presence of scientists, the Apollo program provided some ground-truthing for scientists who used Lunar Orbiter images. Noel Hinners of Bellcomm described the impact of Apollo in a NASA oral history:

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[155] Some scientists also accepted the use of other instruments that produced more concrete data about topography and chemical composition. Vertesi, loc 3330.

> "We learned so much from each of them, including getting surprises. Apollo 16, that was a Fra Mauro [formation] mission. What it turned out to be was not what all the photogeologic interpretations said it would be. So it really did bring home the limits of your ability to interpret orbital photography in terms of what's actually on the ground. Even today as you look at both lunar and planetary photography, Mars photography, and you listen to interpretations, you somewhat shake your head and say, "Yeah, you may be right," but you may not be if you really go down there and look on the surface. Orbital photography has come a long way but it still has its limits in your ability to interpret in very concrete terms what's actually there on the ground."[156]

The technology on Lunar Orbiter enabled scientific exploration in important ways, but the limitations of that technology also constrained the knowledge production efforts of the scientists. The proxy-scientists on the Apollo missions were helpful, but they were still in most important respects a remote presence for Earth-bound scientist-explorers. The success of this collaboration may have demonstrated to scientists that ground-truthing could in fact be done through remote presence. Interpreted this way, the crewed Apollo missions take on a new sort of significance in the history of exploration. After Apollo, robots became sophisticated enough to

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[156] Hinners, p. 23; Hinners' phrasing is confusing here. Apollo 16 did not visit Fra Mauro but landed in the Descartes Highlands. Orbital photography had led scientists to believe that these two areas were geologically distinct. But analysis of rocks from Descartes revealed that they were in fact very similar to the rocks brought back from Fra Mauro on Apollo 14. It has been suggested that the error was due to overreliance on Earth analogues for analysis. For discussion of the geology involved here, see Richard W. Orloff and David M. Harland, *Apollo: The Definitive Sourcebook* (Berlin: Praxis Publishing Ltd., 2006), pp 483-483; and the discussion of Apollo 16 breccias in Stuart Ross Taylor, *Lunar Science: A Post-Apollo View* (New York: Pergamon Press Inc., 1975), pp 215-218.

provide most of the benefits of ground-truthing provided by the astronauts. Exploration teams in later missions used orbiters, landers, and rovers to take direct control of planetary field science for themselves. Limited as the technology may have been, Lunar Orbiter was an early experiment in the practices that came to define exploration in the twentieth century.

Conclusion - Robotics, Telepresence, and Scientific Exploration in Space

Not every planetary scientist has thought of themselves as an explorer, and this was certainly true in the 1950s and 1960s. But the conversations in Iowa and the AAS symposium, along with remarks in the introductions of scientific journals and books from the era, show that many of these scientists had very clear ambitions and self-conceptions. Many of those who worked with Lunar Orbiter believed that they were participating in a process of scientific exploration—explicitly stating that they were working in the tradition of Magellan, Darwin, and Lewis and Clark. The surveillance of the lunar surface prior to the Apollo landings filled a role that existed in the missions of those explorers. The scientific practices of the lunar scouts were built on traditions of geologic field science conducted through aerial photography, combined with practices used in telescopic observation. Kodak's cameras were an enabling factor that allowed them to extend these practices to another world.

Other sciences that use remote sensing tools can provide insight into how these technologies changed the process of scientific exploration in the twentieth century. Robert Ballard, for example, has discussed the dawn of robotic exploration extensively, and pioneered its use in the deep ocean. He described a concept he called "telepresence," where he felt as though these technologies allowed him to perform the tasks of field science almost as if he were there in person. In Ballard's mind, the aquatic robots became extensions of himself.[157] Was this sense of telepresence there at the beginnings of robotic space exploration? The Lunar Orbiter spacecraft seem to have given scientists and operators a very limited sense of telepresence at best. But the hints of what the technologies were capable of were there. Art Cosgrove's near-real-time images on the oscilloscope provided a glimmer of in-the-moment visual presence. Even spending extensive time with the final photographs, as Farouk El-Baz did, had the potential to spark some sense of "being-there." I was able to handle large prints from the Lunar Orbiter program in the archives of the Goerge Eastman Museum in Rochester, of the same sort used by scientists and Apollo mission planners. The size of the prints meant that when I inspected the images closely, the surface of the Moon took up my entire field of vision. The longer I inspected the images, the more the lunar surface became the only thing I was really aware of. It is easy for me to understand what Harold Urey meant when he talked about our ability to fly above the ground in our heads.

Telepresence became a stronger part of space exploration as technologies became more advanced in the late twentieth century, and eventually it became an important aspect of the ground-truthing process. The participants of the Iowa Summer Study anticipated this with some accuracy, describing a type of

[157] Robert D. Ballard, "Ocean Exploration: Past, Present, and Future," *Bulletin of the American Academy of Arts and Sciences* 68, no. 2 (2015).

"telepuppet" that could enable people to "extend [their] senses and mechanical abilities," while allowing them to make use of the qualities that distinguished humans from robots such as "judgement, adaptability, improvisation, and selectivity."[158] Later space explorers employed these types of robots to great effect. Carl Sagan described his experience working with *Viking* as being somewhat like spending a year on Mars.[159] But while scientists could use *Viking* to extend their arms to Mars, the robot was an immobile platform. More recent Mars rovers have greatly enhanced the independence that scientist-explorers have on other worlds. The scientists and spacecraft operators of the MER program and later Mars rovers have been able to conduct the type of investigation that Daniel Hale lamented was available to Darwin but not twentieth century selenologists.

Janet Vertesi's work shows that telepresence in these Martian expeditions is more often indirect—built from numerous experiences and the larger picture of the project—than it is a visceral feeling in the moment.[160] It is revealed in the vocabulary used to talk about the workflows of science and operations, and the sense of place

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[158] National Research Council, Chapter 11, p 7; the term "telepuppet" is attributed to astronomer Fred Whipple.
[159] Carl Sagan, *Pale Blue Dot: A Vision of the Human Future in Space* (New York: Random House Publishing Group, 1994) Kindle, loc 192.
[160] While it was less common, Vertesi describes how many team members felt viscerally connected to the rovers, and how this feeling became a part of exploration processes. Apparently, it was common practice to plan maneuvers by using their bodies to imagine being the rover.

this vocabulary produces. Vertesi notes that this sense of place is strongly interwoven with the decision-making process for the rovers. It is instrumentalized to bring together team members who may be from vastly different disciplines, or even living and working across vast distances. Team members may be in different cities, but together, they are on Mars working towards the same goals.[161] In meetings to discuss planning, Vertesi observed that mission planners described the rover and its location in first-person terms. They used images from the rover and from orbiters to "give the team a sense of 'where we currently are' and 'where we're heading.'"[162] Orbital scouts remain an important part of the exploratory process. One of the orbital images Vertesi writes about was from a 2006 report on the *Opportunity* mission. It shows an oblique view of a crater, annotated with text and arrows that point out the location of the rover and target features. This oblique orbital imagery, viewpoints from the rover, and first-person language work together to create a sense of place, and a sense of presence in that place through the body of the rover.[163] This

[161] Vertesi, loc 656.
[162] Vertesi, loc 678.
[163] Technology has only intensified this feeling over time. Telepresence has also become more accessible to people beyond the scientists and engineers on the exploration team. The combination of new camera technologies and more affordable virtual reality headsets have enhanced telepresence to an almost unbelievable degree. I can pull up a high resolution, 360-degree panorama of the Martian landscape, put on my virtual reality headset, and look around as if I am standing on the surface itself, hearing sound recorded at that location. The feeling of "being there" is visceral, and what I am seeing and hearing is a real place. It just happens to be an incomprehensible distance away from my computer.

creates a shared perspective for the team that enables them to understand important mission context and make decisions. A similar sort of process can be seen in precursor forms throughout the lunar exploration missions of the 1960s.

One thing that most differentiates robotic space exploration missions from exploratory missions in previous centuries is the scale of the human element—at least in the popular and conventional historical narratives. On every one of the missions mentioned here, large collections of people worked together to extend their senses toward other worlds and to conduct field science remotely. There was no single intrepid explorer—the heroic man standing on the bow of the ship or hacking their way through the jungle. But the robots themselves have been anthropomorphized in the popular press and NASA communications. They have been granted agency in the press and in historical narratives. In these representations, one can almost glimpse the heroic explorers of old. But the idea of the single heroic explorer may have always been mythical, partly a side-effect of hierarchical social norms, partly a publicity tool. In every case, behind the public face (human or mechanical) have been groups of people working together in common purpose.

Teams composed of dozens, hundreds, or thousands of people worked together to assemble and maintain sailing vessels—and to keep robots on the right trajectory and performing the right tasks. Across the centuries, they encountered similar challenges, reacting to unexpected environmental conditions, technological failures, and human drama. The reactions of spacecraft operators did not look quite the same as those of ship pilots guiding a ship between icebergs. But at times in the Lunar Orbiter story, especially as Lunar Orbiter I operators struggled to avoid the danger of the sun's rays, the problems they faced seemed akin.[164] Regardless of how convincing these parallels are, many of the space scientists of the twentieth century conceived of themselves as explorers. The gravity of this self-perception can capture scientists that may not have shared it, revealing that they unknowingly played a role in a larger historical process that was given new significance by its later players.

The technologies of the twentieth century allowed these explorers to visit new places in very different ways than their predecessors. They visited the far side of the Moon, the sands of Mars, the volcanoes of Io, and the clouds of Titan—without leaving their home planet. They took on different types of risks than other explorers, but they took risks all the same. Their reactions to unexpected conditions

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[164] Another notable feature of exploration through remote sensing is the fact that the time it takes to receive and relay commands is sometimes long. Reaction times are dulled by distance. This can be seen as a similarity to previous episodes of exploration in some ways – messages took a long time to reach expeditions before the telegraph and radio—but what makes robotic exploration unique in this respect is that the reaction times of the explorers themselves is dulled. However, because the Moon is close by, this effect is less of an issue than in the case of the MER mission or Voyager, and some of the similarities to historical patterns of exploration can be seen in sharper relief.

took into consideration the environment, the capabilities of their vehicles, and the unique timescales and cadences of their missions. They learned something new about themselves, and their activities created connections across cultures. They shared their discoveries—both scientific and personal—with people back home, generating potential energy for further exploration and frontier expansion. New worlds have crystallized in the popular imagination. Some of these new worlds are still cloaked in mystery, awaiting investigation by future scientist-explorers.

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