Keynote Address

Space, Time, and Space Architecture

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Abstract

Space and Time are inextricably connected. Humans' earliest indicator of the passage of time was surely the apparent movement of the sun through the sky from sunrise to sunset. The day/night cycle was just the first metric for the passage of time based on the passage of celestial bodies through space. Following the measure of the day, the next longest metric would be the month, the unit of a lunar calendar, based upon the revolution of the Moon around the Earth. Finally, the measure of a year reflects one revolution of the Earth around the Sun. Each of these measures brings profound implications for all forms of life on Earth, perhaps most particularly human life as our species expands into space.

These fundamental measures of time provide the raw material for many concepts in astronautics, astronomy, mathematics, physics, and space mission design. Rather than trace the chronological or historical development of these disciplines, this essay follows an associative pattern to describe the linkages and leaps among these ideas, associated precepts, and the phenomena they describe.

Keywords: Spacetime, Lunisolar Calendar, Synodic Period, Human Mars Mission, Space Architecture

Nomenclature

Δv	Delta v, the change in velocity necessary for a spaceflight from one set of coordinates to another serves as a first order indicator of the propellant mass that will be required.
AIAA:	American institute of Aeronautics and Astronautics
Aphelion:	Where a celestial body or spacecraft is farthest from the Sun in its orbit.
ECLSS:	Environmental Control and Life Support System
ISS:	International Space Station
JPL:	NASA's Jet Propulsion Laboratory in Pasadena, California
JPS:	Jewish Publication Society
JSC:	NASA's Johnson Space Center in Houston, Texas
LEO:	Low Earth Orbit
MSIS:	Man-System Integration Standard, NASA Standard 3000c(1995).
NASA:	National Aeronautics and Space Administration
NEO:	Near Earth Object, typically an asteroid
NIAC:	NASA Innovative and Advanced Concepts (a classic acronym within an acronym in NASAspeak)
Perihelion:	Where a celestial body or spacecraft is closest to the sun in its orbit
PHI:	Proportions, Harmonies, and Identities
RAP:	Robotic Asteroid Prospector
SAE:	Society of Automotive Engineers
Spacetime:	Einstein and Minkowski's relativistic construct for a 4-Dimensional integration of space and time.
Stadion:	Ancient Greek measure of length 155 to 160 meters. Plural is stadia.

1. Introduction

Probably the most important and influential architectural history book published in the 20th Century is Siegfried Gideon's Space, Time, and Architecture. The theme of this 2022 PHI Conference is Time and Space. Out of respect for Gideon and humanistic vision of this conference, the title of this keynote is Space, Time, and Space Architecture.

Space and time are inescapable. At the most fundamental and formative level of human experience, we inhabit both. We inhabit volumetric space measured in square meters (m^2) on the surface of the Earth and measured in cubic meters,

m^3 in outer space . We measure our lives by time with a granularity of the periods of revolution of the Earth around the Sun, broken down into digital calendars, often by the quarter-hour (or for lawyers, by the sixth of an hour). From the Earth's day/night cycle to the cosmic rays that bombard our chromosomes triggering potential mutations, the dynamic forces of space *writ large* are all-pervasive.

This essay connects to leading pioneers of astronomy, engineering, and physics. These figures include Eratosthenes, Copernicus, Galileo, Kepler, John Harrison, Buckminster Fuller, among others.

Our knowledge of space leads to the concept of space-time, which yields several understandings. These insights range from astrophysics to the human factors of habitability. Einstein's vision of *spacetime* (single word in good *Deutsch* style) in his Theory of Special Relativity (1905) plus Special Relativity (1915) laid the foundations of modern physics. But more than that, relativistic spacetime reveals a spectrum of physical and temporal reality that suggests infinite intersections between time and space, yielding a profound interconvertibility between them. Einstein is credited with the assertion, "It is in consequence of this that space and time are welded together into a uniform four-dimensional continuum" (although Herman Minkowski was the first to declare that space and time together make the 4 -dimensional "independent reality") (Overduin, 2007).

Einsteinian spacetime has emerged as a metaphor endemic to most themes in science fiction. Where would Start Trek go without warp speed—a multiple of the speed of light (c) before the end of the TV season?

At the opposite end of this spectrum arises the formulation: how much time can a human live in a space of a specific, confined volume? At the Newtonian level, this question poses profound issues for how long a space mission can endure. Given a constant velocity or constant acceleration of a given propulsion system and propellant supply, the length of a human mission will be limited by the explorers' ability to tolerate and hopefully thrive in their living and working environment.

2. The Field of Space Architecture

My field is Space Architecture. I am a licensed architect who has devoted his career to researching and developing design concepts for crewed spacecraft, space habitats, space stations, and lunar and planetary bases. That professional practice made me one of the "founders" of Space Architecture as a discipline. Much of this work focuses on research for human living and working environments in space, including the microgravity of orbital space stations, and the partial gravity of Moon and Mars habitats and bases.

I wrote this keynote for the PHI Congress in attendance here in Oporto. But in a broader sense, I wrote it for new and future generations of Space Architects. I have become deeply concerned that among the new wave of young people entering our nascent profession, too many are uninformed about the topics of space and time that I present in this essay.

This situation concerns me because I fear that they are entering the profession of Space Architecture without the essential baseline of knowledge about the phenomena of space, time, and the movement of celestial bodies and spacecraft that are so central to our human spaceflight enterprise. The new generation has tremendous enthusiasm, energy, and persistence that I admire and with which I identify from my own misspent youth. What I fear is that while they make gorgeous presentations through sophisticated computer-aided rendering and additive manufacturing (also known as 3D printing) they may not grasp the physics, environmental control and life support chemistry, and structural engineering necessary to actually support human life, health, and productivity in the extremely hostile space environment. The crux of the matter is that the essential function of the architecture profession and the requirement to attain licensure is the knowledge and ability to protect the health and safety of the public. To put it more bluntly, many of the designs I have seen in recent years are highly artistic and beautiful but are neither evidence-based, nor research-based, nor functional. They would not protect the health and safety of a space crew.

Therefore, the leading principle of Space Architecture's professional standard of care must be to protect the health, safety, and life of the people in space. In order to meet this professional standard of care within the larger context of orbits, planetary surfaces, and the overall space environment within the Solar System, the second principle for Space Architects is to GET THE PHYSICS RIGHT. These principles of Space Architecture are necessary to design habitats and spacecraft that will take an effective, pragmatic, and realistic approach to protect the crew in the extraordinarily hostile space environment. In responding effectively to the orbital mechanics and physical environments of planets and their moons, the Space Architect must comprehend the exposures, hazards, and potential threats that may affect any crew, location, logistics mission, operation, orientation, protocol, resources, spacecraft, space habitat, or structure. This comprehensive understanding should be cognizant of Buckminster Fuller's Dymaxion Principle and apply it (Fuller, Marks; 1965; Fuller; 1969):[1]

> **Comprehensiveness**—seeing the big picture, the integrated system with all it entails,
>
> **Anticipation**—foreseeing what the building, the house, the invention, the operation, the system will need in its full development, and
>
> **Design as Science**—the idea that not only should there be a rational and empirical basis for design decisions, but that it should derive from a testable, empirical, and "provable" basis.

This last point is especially relevant to Space Architecture today. The act and the art of designing are fun, and I always found them to serve as the most gratifying part of the job. Yet, unless there is an empirical, evidence-based foundation for a design in Space Architecture, it can be no better than any ego-driven, glossy magazine pictorial. Unless it brings true insight into human needs in all their complexity, it can be no better than any unselfconscious engineering scheme that fails to consider its human impact and consequences for the crew***.***

3. Basic Relationship Between Time and Space

Perhaps the simplest example of the relationship between time and space is distance when defined as velocity x time = distance. This definition may seem tautological or self-referential given that velocity is distance/time. Yet motion is essential to the relationship of time and space. Motion cannot happen without time. As Albert Einstein teaches us in Special Relativity, all measures of velocity are, well, *relative* to one another, including not moving at all. Given Michaelson and Morley's measure of the speed of light, as 300,000 km/sec (or 186,000 ft/sec) and the time it takes to travel from its source, we can measure the distance to astronomical objects. The light travels for years, ergo light years.

And what about these objects in space? How does space and time and the motion and light that mediates them inform us about bodies in space? The earliest application may appear in the ancient Greek's proof that the Earth is round, or more precisely a sphere. Around 700 BCE, the Greeks made three observations:

1. When ships sailed away at sea, they appeared to sink lower and lower until they disappeared beyond the horizon.
2. When people travelled north or south, they saw different constellations in different altitudes in the sky.
3. When a lunar eclipse occurs, the Earth's shadow projected upon the Moon's surface is always a curve. The only object around which the light could always project such a curved shadow from any direction is a sphere, as shown in FIGURE 1.

FIGURE 1. Partial lunar eclipse as the ancient Greeks might have seen it (16 June 2019). Wikimedia Commons.

Eratosthenes refined the definition of the spherical Earth and provided a remarkable accurate measurement of the Earth's circumference. This measurement depended first upon the apparent movement of the Sun through the sky and the fact that its highest altitude occurs at the midpoint of its transit, noon. As shown in FIGURE 2, Eratosthenes measured the angle of the shadow that a stick of constant height cast in Alexandria, Egypt and then marched south 5,000 stadia or 800 km very close to the Tropic of Cancer at Syene (today's Aswan) where the Sun stood directly overhead on the summer solstice. There he took the measurement using the same stick and the same angle measurement tenue a second time. Based upon these results, he computed the angle from the center of the Earth to the two stick positions, and from that calculated the circumference of the Earth with surprising accuracy. He calculated the circumference of a meridian at 252,000 stadia (where a stadion is estimated by archeologists and classical scholars at 155 to 160 meters). That value converts to 40,032 km (25,020 statute miles).

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[1] This paper includes multiple lists of arguments, evidence, observations, and precepts. These lists are not quotations but are my interpretations or summaries of these points.

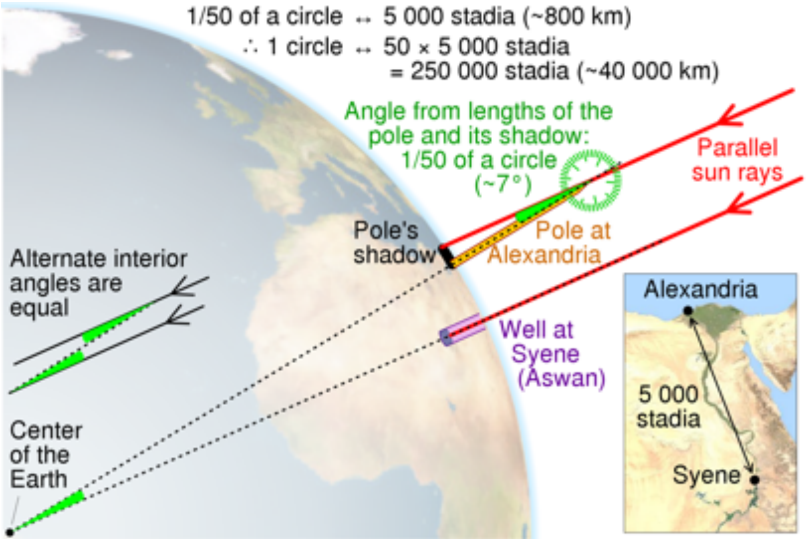

FIGURE 2. Diagram of Erasthonene's Method of Calculating the circumference of the Earth, according to Cleomedes' simplified version, based on the approximation that Syene is on the Tropic of Cancer and on the same meridian as Alexandria. Courtesy of Wikimedia Commons.

4. Lunar Calendars

Second only to the evidence of the Sun's apparent movement through the sky in the daytime was the Moon's actual and apparent movement through the sky in the day and the night. Observations of the Moon's cyclic motion led to the development of lunar calendars, which may have been the first calendars invented. At least three ancient lunar calendars appear to remain in use today: Chinese, Haida, and Hebrew. Both the Hebrew and the Chinese zodiacal calendars are based upon principally lunar models with some solar-influenced interpretations. It is difficult to determine which may be the first or oldest, but at least in terms of the documentation available, a common interpretation traces the Hebrew calendar's origin to Exodus 12:2 (Parshah Bo), which recounts Passover and the departure from Egypt (generally dated 1447-6 BCE):

הַחֹדֶשׁ הַזֶּה לָכֶם רֹאשׁ חֳדָשִׁים
רִאשׁוֹן הוּא לָכֶם לְחָדְשֵׁי הַשָּׁנָה

> This month shall mark for you the beginning of the months;
>
> it shall be the first of the months of the year for you (JPS, 2006).[2]

The Hebrew year is made up of 12 months of either 29 or 30 days. Because these 12 months do not add up to the 365.25 days of the Earth's orbit about the Sun, periodically it is necessary to add a 13th month, known as Second Av.

5. Solar Calendar and Sidereal Year

The Solar Calendar is based upon the movement of the Earth around the sun which takes 365.25 days. This measure leads to the addition of a leap day every four years, during leap year. However, the Solar Year is not the only metric based upon the motion of the Earth around the Sun. In comparison, the Sidereal Year is measured against the fixed stars relative to the Earth's motion, so it is 20 minutes longer than the Solar Year. The Sidereal year was first identified by Hipparchus through his observation off the precession of the equinoxes. The movement of the Earth through space is the same in both measures of a year, but the frame of observation differs, providing a modest relativistic example.

In the Solar year, as observed by cultures all over the Earth, the solstices (longest and shortest days of the year) and the equinoxes (literally equal night) widely became special occasions for holidays, marking the "quarter-points" of the year. Some cultures created special occasions on the cross-quarters (also known as "eighth-points") halfway between the solstices and equinoxes. For example, Shakespeare commemorated one such cross-

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[2] Passover marks the beginning of the religious year. Rosh Hashanah (literally "Head of the Year") marks the beginning of the civil year.

quarter in A Midsummer Night's Dream marking the half-way point between the summer solstice and the autumnal equinox. Midsummer night[3] was a popular pagan festival in pre-Christian Europe and evidently the tradition continued in some manner into the Elizabethan era. Shakespeare opens the play (1600, A1 S1):

> THESEUS
>
> Now, fair Hippolyta, our nuptial hour
>
> Draws on apace; four happy days bring in
>
> Another moon: but, O, methinks, how slow
>
> The old moon wanes!

I infer that the characters celebrate the holiday of Mid-Summer Night on the first new Moon following the Mid-Summer cross-quarter. In a similar manner, potential cross-quarter holidays such as Beltane (May Day), All Hallows Eve (Halloween), St. Valentine's Day, and even Easter may have slid around on the lunar-inflected solar calendar. In addition, the irregular changes from the Greek, Roman, Julian, and Byzantine calendars to the Gregorian calendar could have shifted some holiday observances by as much as a month. In this way, the Earth's motion around the Sun—particularly as observed from the Earth—provided a culturally rich calendar to many societies.

6. Copernicus and the Center of the Universe

The Perhaps the most antagonistic controversy in the history of astronomy was the debate over where the center of the universe resided. The traditional view in the Ptolemaic model of the Solar System was that the Earth occupied the center and that all other bodies revolved around the Earth. The politics and religious roots of *who* or *what* occupied the Center of the (known) Universe were vicious. In FIGURE 3 around Peter Apian's (1524, 1545) geocentric model on the left, the circumferential inscription in Latin says:

> COELVM EMPIRVM HABITACVOLVM DEI ET OMNIVM ELECTORVM
>
> The Empire of God is the Divination of God and All are Electors.

Frank Swetz, Pennsylvania State University translates it (Apian, 1524, [Swetz], 2013).

> Habitat of God and the Elected [Saints and Angels].

Clearly, this model was anchored in a religious predetermination about the universe. Although scientists were aware for millennia (Philolaus, c. 470 – c. 385 BCE, Greece) that the Earth is a planet that revolves about the center of the Solar System (Stanford, 2020), Copernicus was the first astronomer with the courage to state it systematically and make rational arguments for his heliocentric theory. Although one of its weaknesses was the lack of new observations to support his claims, the Heliocentric Theory did offer simpler explanations than the Ptolemaic Theory for some existing observations such as retrograde motion of the planets and why Mars and Jupiter appeared larger and smaller at different times. Copernicus' arguments state:

1. The Earth revolves about the Sun. The planets revolve around the Sun in specific orbits for each planet's revolution. The Earth is a planet.
2. The Earth goes through three forms of motion and these motions are simultaneous:
    a. The Earth revolves about the Sun. One revolution equals one year.
    b. The Earth rotates daily upon its axis. One rotation equals one day/night cycle.
    c. Because the axis of the Earth tilts, the surfaces of the planet receive varying amounts of sunlight throughout the year, hence the seasons.
3. The Earth's motion about the Sun affects observations of the planets. It accounts for the appearance of retrograde motion of the other planets.
4. The stars appear fixed in the sky because they are so much farther away from the Earth than the Sun or the planets. Parallax is not observed because the "fixed stars" are so far away.

Copernicus's heliocentric theory ran into stiff opposition from the establishment of his time. The adherents of Ptolemaic geocentrism considered their dogma as the infallible word of God and Copernicus's heliocentric theory as equivalent to blasphemy. FIGURE 3 shows a comparison of the two theories with diagrams from De Revolutionibus Orbium Coelestium. In the geocentric model on the left, the order of the celestial orbs moving outward from the Earth is: "Luna, Mercvrii, Venevs, Solis [the Sun] Jovis, Saturni, and Firmamentu" with the stars drawn onto that circular band, In the heliocentric model on the right, the Earth's orbit

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[3] Midsummer night is known in Gaelic as Lughnasadh or Lughnasa and in Old English as Lammas.

is clearly distinguishable as the fourth ring with the orbit of the orbit of the Moon highlighting the position of the Earth. The third and fifth orbits intersect the limits of the Moon's orbit about the Earth, demarcating the zone of cis-lunar space.

One aspect of Copernicus that is often overlooked is how poetic his language is. This passage is how he introduces the celestial orbs in his heliocentric model from the outermost inward:

> The first and highest of all is the sphere of the fixed stars, containing itself and all things: and therefore immovable. that is, the universal place, to which the motion and position of all the other stars are compared. For some think that it is also changed in some way: we will assign another cause, why it appears so, in the deduction of the motions of the earth.
>
> [The sphere of the fixed stars] is followed by the first of the planets, Saturn, which completes its circuit in 30 years. After Saturn, Jupiter accomplishes its revolution in 12 years. Then Mars revolves in 2 years. The annual revolution takes the series' fourth place, which contains the earth, as I said, together with the lunar sphere as an epicycle. Venus is reduced to the fifth place in the ninth month. Lastly, the sixth the place Mercury holds, eighty days peacefully running in a circle.[4]
>
> At rest, however, in the middle of everything is the sun. For in this most beautiful temple, who would place this lamp in another or better position than that from which it can light up the whole thing at the same time?

FIGURE 3a. Ptolemaic model of the Aristotelian/Christian Solar System. Credit: Peter Apian (1524, 1545). Cosmographica. https://www.maa.org/press/periodicals/convergence/mathematical-treasure-peter-apian-s-cosmographia

FIGURE 3b. Diagrams of the Solar System from Copernicus' thesis: De Revolutionibus Orbium Coelestium (1543) showing the planets orbiting the Sun and the Moon orbiting the Earth.

7. Galileo

Great scientists followed Copernicus in advocating for the heliocentric theory, Galileo perhaps greatest among them. Galileo discovered the moons of Jupiter, and recognized their motion about Jupiter as a sub-scale model of the Solar System. FIGURE 4 shows three Jovian moons as Galileo might first have seen them. This discovery involved a vital set of observations of small celestial bodies revolving around a much larger body, providing an irrefutable "existence proof" to which to compare the Solar System.

Galileo encountered much the same type of dogmatic rejection as Copernicus, with the persecution of a church trial and the punishment of house arrest. The Church at that time viewed his claims as tantamount to

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[4] Copernicus introduces Mercury in his De Revolutionibus (1543) in Latin as "Sextum denique: locum Mercurius tenet, octuaginta dierum pacio circu currens." Pacio means peace or to peace. However, in all the modern transcripts I found, the transcriber/translator (or her spelling checker) adds an "s" at the beginning, changing it to "spacio" which means space. Although it may seem consistent with the subject, inserting the word "space" is completely superfluous, whereas "peace" or "peacefully" adds meaning and richness.

heresy.

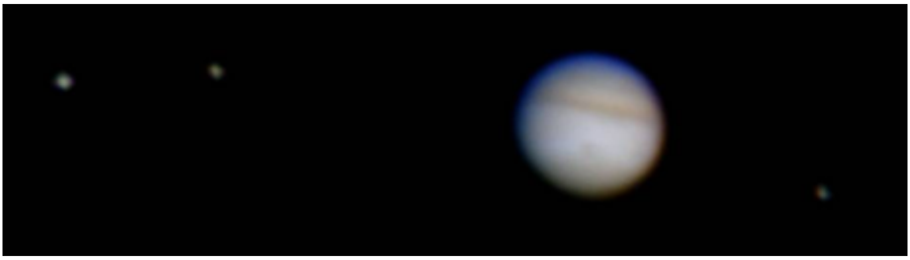

FIGURE 4. Photo of three of the four Galilean moons of Jupiter seen through an amateur telescope. much as Galileo might have first observed them. Credit: Thomas Bresson, NASA. https://www.nasa.gov/feature/410-years-ago-galileo-discovers-jupiter-s-moons

FIGURE 5a shows Galileo's sketches of what he saw through his telescope similar to FIGURE 4. Initially, he kept seeing only three moons. FIGURE 5b shows Galileo's model of the Solar System including the four Moons of Jupiter illustration but excluding the "Firmamentu" of fixed stars; he recognized that they are not part of the Solar System. FIGURE 5c shows Galileo's diagram of the seasons based on the position of the Earth in its orbit and its tilt.

Although most of the attention Galileo receives is for his brilliant and heroic support of the heliocentric theory, another of his explanations in the Dialogue of the Two Chief Systems reflects phenomena that affect almost every living thing on Earth: the seasons and how the Sun's annual cycle takes it below the ecliptic. People commonly think of seasons and the change of seasons as "the time of the year."

The passage of time does corollate *indirectly* to the seasons, but Galileo explained them in terms of the position of the Earth in its orbit with its tilted axis of rotation. Copernicus documented the tilt in the Earth's axis in De Revolutionibus, but Galileo was the first to elucidate why the Earth has four seasons every year based on scientific observations. In the Dialogue, Galileo states that the axis of the Earth is tilted 23.5°. Space and time.

FIGURE 5a. Galileo's first sketches from his observations of the Jovian moons. NASA: https://solarsystem.nasa.gov/news/307/galileos-observations-of-the-moon-jupiter-venus-and-the-sun/

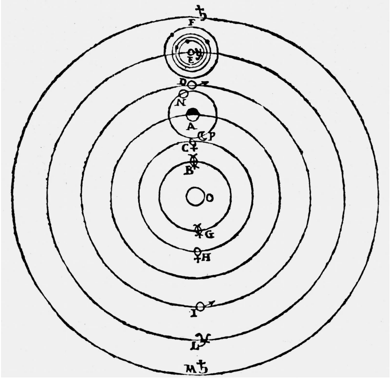

FIGURE 5b. Galileo's Solar System with Jupiter's four moons and without the fixed stars of the Firmamentu.

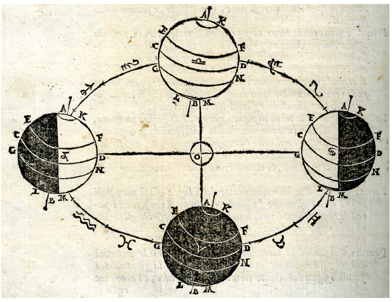

FIGURE 5c. Galileo's Diagram of "The Four Orbs" showing the Earth, tilted on its axis, in four position around the Sun. From the Dialogue.

8. Kepler's Laws of Ellipses/Orbits

Using meticulously documented, huge sets of observations from the Danish astronomer Tycho Brahe, Johannes Kepler discovered three laws of planetary motion that refined both Copernicus' and Galileo's work.

Law 1. Every planet's orbit is an ellipse in which the Sun sits at one focus and there is a second focus at some distance from the center of the Sun [If a truly circular orbit exists, it would still be an ellipse, but with both foci at the same location.]

Law 2. A line (the radius vector) from the center of the Sun to the center of the planet sweeps out equal areas in its orbit in equal times as the planet revolves about its two foci. See FIGURE 6.

Law 3. The square of a planet's orbital period is proportional to the cube of the semi-major axis of its orbit.

In FIGURE 6 illustrating Kepler's Second Law, the blue pie shapes are all equal in area. The difference among them is their distance from the Sun. The speed of revolution varies, with the fastest speed (distance traveled in time *t*) at perihelion and slowest speed at aphelion.

Kepler's second law offers a fascinating example of the relationship between time and space. One way to understand it is that the *rate* (dA/dt) at which a planet sweeps out an area in its orbit is *constant.* This perspective reiterates the precept (in the introduction) that distance = velocity x time. Equal time, equal area (space).

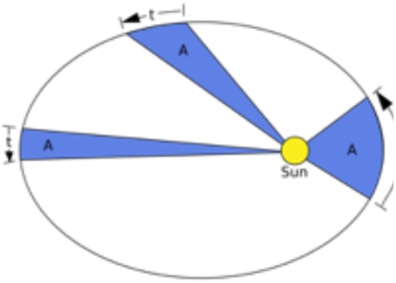

FIGURE 6. Diagram illustrating Kepler's Second Law. Credit: Wikimedia Commons.

9. The Longitude Prize

The previous anecdotes have all placed the primacy of Space ahead of Time. However, in this exemplar, time is the key to finding a physical position in space. That position was the location of the ship with respect to its East/West travel, its *longitude.* Once frequent and regular transoceanic navigation began in the 16th century, the ability to find the longitude of a ship's position became crucial to safe and efficient ship-handling. Finding Latitude had ceased to be a problem with the advent of the quadrant and the sextant in earlier centuries that navigators used to "shoot the sun" or the "fixed stars" at night (mainly Polaris, the north pole star). To determine longitude accurately and precisely, navigators needed a different approach. See FIGURE 7. Recognizing that because the Earth rotates continuously about its axis in 24 hours, the scientists of the day sought to reconcile this passage of time with the rotating meridians of longitude.

This feat required a highly accurate and reliable clock, which became known as a chronometer. The governments of several European countries offered prizes to find a solution for the longitude problem beginning in the mid-16th century.

However, it was not until the British government offered its Longitude Prize in 1714 that the battle was truly joined. Britain was the most technologically advanced of the great sea-going powers of that century. The *Longitude Board* could award various sums of money for technological improvements in timekeeping at their discretion.

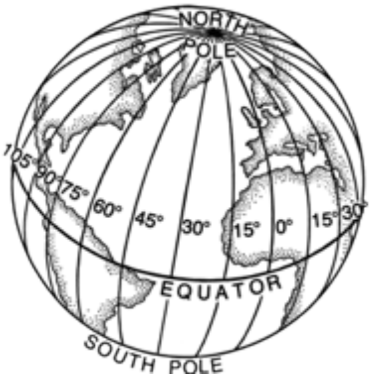

FIGURE 7. Meridians of Longitude. Credit: Pearson Scott Foresman, Public Domain.

FIGURE 8. John Harrison's H5 Chronometer at the Science Museum, London, UK. Credit: Racklever, English Wikipedia. Open license to all.

After developing four prototypes over 36 years, John Harrison "won" the Longitude Prize with his H4 chronometer of 1761. FIGURE 8 shows the H5 Chronometer. Harrison won a total of £23,065 in incremental prizes over this period, the largest amount awarded to any inventor.[5]

The Royal Navy quickly adopted this revolutionary device. They established a system in which each ship carried two chronometers, set to the same time at the beginning of each voyage by an official chronometer master. Each clock was locked in an oak box to make it tamper-proof. The Captain of the ship took responsibility for winding the spring regulated chronometer. If the two timepieces diverged in their timekeeping, he took the average between them. At the end of a voyage he returned the chronometers to the time master.

By knowing the time to a high precision, it became possible to calculate the longitude from shooting the Sun at noon. The marine chronometer enabled determining longitude accurate to half of 1° (30 minutes of longitude). Many improvements on Harrison's chronometers followed quickly from inventors around Europe. While there is debate about which advanced chronometer laid the foundation for modern navigation (until the advent of electronics), the significance of Harrison's contributions to the Longitude Prize is indisputable.

10. Synodic Period of Asteroids and Planets

Marine navigation is not the only situation in which timing is primary to the task. Another example comes from spacecraft missions to asteroids. At the level of celestial mechanics for exploring asteroids exists another intersection of space and time—the synodic period[6]—that derives from the tyranny of orbital mechanics. As of this writing, there are about one million known asteroids orbiting the Sun, and many more yet to be discovered. Some tens of thousands of known asteroids pass close to the Earth, and so are called Near Earth Objects (NEOs). To visit an asteroid when departing from Earth orbit, timing is everything: *when* you go determines *where* you can go. FIGURE 9 comprises a plot of synodic periods between the movement of planets and asteroids, and the (green) curve that arcs upward from left to right represents asteroids. The other three curves represent the Earth, Mars, and Venus, which is always a favorite for fly-by gravity boosts.

This table of Synodic Periods comes from our 2013 Robotic Asteroid Prospector (RAP) report to NASA. The project was to design a spacecraft that could explore asteroids and extract exploitable quantities of resources starting with water to be returned to customers on the Moon, Mars, or in orbit around those bodies. The challenge for RAP was not just to fly to the target asteroid, but to perform useful work of prospecting for resources, extracting them, , and then flying this cargo to a spacetime coordinate where there are industrial facilities to process it or customers who can use it. These customers would most likely need to be people living in a permanently inhabited outpost on a moon, planet, or in orbit around such a celestial body. All these factors combine to emphasize the importance of navigating the synodic period between asteroids and destinations. The key to navigating the trajectories between planets or asteroids is to understand the synodic period. If I may indulge in one equation, the synodic period S is defined in EQUATION 1, where E is the period of the Earth's orbit and A is the period of the asteroid's orbit.

EQUATION 1

$$\frac{1}{S} = \left|\frac{1}{\frac{1}{E} - \frac{1}{A}}\right|$$

Because of the great expense of spaceflight and the imperatives of the rocket equation that can demand a mass of propellant orders of magnitude larger than the payload, the less Δ*v* required to transit from the point of extraction to the customer, the better. This lesson in space economy means that the customer must reside in space. When thinking of gravity as part of the curved fabric of spacetime, this perspective shows that the best place to deliver it would be one with the shallowest gravity well. That could mean moons of Mars, Phobos or Deimos, or the Earth's moon, or perhaps the minor planet/largest asteroid Ceres. In conducting the RAP study, we found no scenario in which it would be profitable to return minerals, metals, or water to the surface of the Earth or even to low Earth orbit (LEO).

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[5] I visited the Greenwich Observatory, Greenwich, UK in 1997 and viewed Harrison's H4 chronometer in an exhibition commemorating the longitude prize competition.

[6] The **synodic period** is the amount of time that it takes for an object to reappear at the same point in relation to two or more other objects. The time between two successive oppositions or two successive conjunctions is equal to the synodic period." Courtesy of Wikipedia. For example, the next two oppositions of Mars are 2022-12-08 and 2025-01-16.

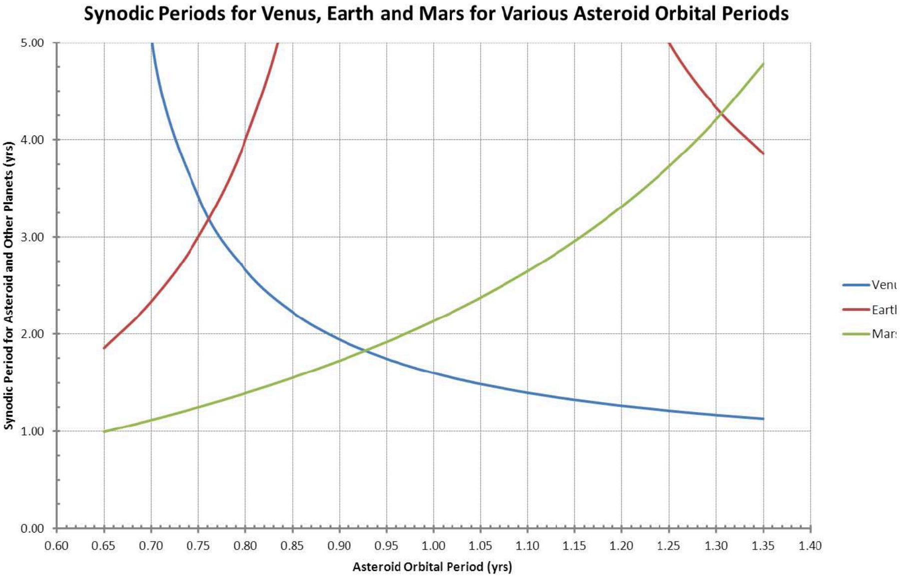

FIGURE 9. Synodic periods for planets and asteroids, (Cohen, James, Zacny, Chu, Craft, Blair; 2013; p. 53).

FIGURE 10 shows a 3D view of the inner Solar System, generated using the "Small Body Browser"[1] at NASA's Jet Propulsion Lab. The wider white orbit represents the asteroid 2 Pallas, which tilts 34° rom the ecliptic plane in which the inner planets all orbit.

Try to visualize the synodic relationship between the Earth and 2 Pallas. A spacecraft intended to navigate to a rendezvous with 2 Pallas would need to depart the Earth when the Earth passes closest to 2 Pallas' orbit. Also, 2 Pallas would need to be headed toward that closest space and time coordinate with the Earth to make the rendezvous feasible in term of the propellant expenditure required. 2 Pallas appears in white; the vertical white lines portray its tilt from the ecliptic.

As part of the NIAC grant from NASA for RAP, it was necessary to design a credible spacecraft to transit through such a synodic period from the Earth to an asteroid of potential interest. Our team conceived a spacecraft design that incorporates several innovative features, shown in FIGURE 11. The propulsion system consists of a pair of solar dynamic parabolic concentrators. These concentrators are pointable and rotatable using a system of alpha and beta joints that work similarly to the ones on the ISS. The concentrated sunlight serves three functions:

1. The concentrated sunlight drives the engine through which RAP expels super-heated water as its primary propellant mass.
2. The concentrated sunlight drives an electric power generator that provides power throughout the spacecraft. This power can be stored in batteries that can heat coils in the engine and in auxiliary thrusters that can operate the spacecraft at low speeds.
3. The concentrated sunlight can be directed through a system of prisms and mirrors to the surface of a captive asteroid where it can melt or sublimate off any water ice or extraction. It may also prove useful for extracting any metals or minerals with a relatively low melting point.

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[1] Known originally as the "Small Body Browser" the formal name of this online tool, is the "Small-Body Database Lookup Orbit Viewer," an exceedingly rare instance in which there is no approved acronym in NASAspeak.

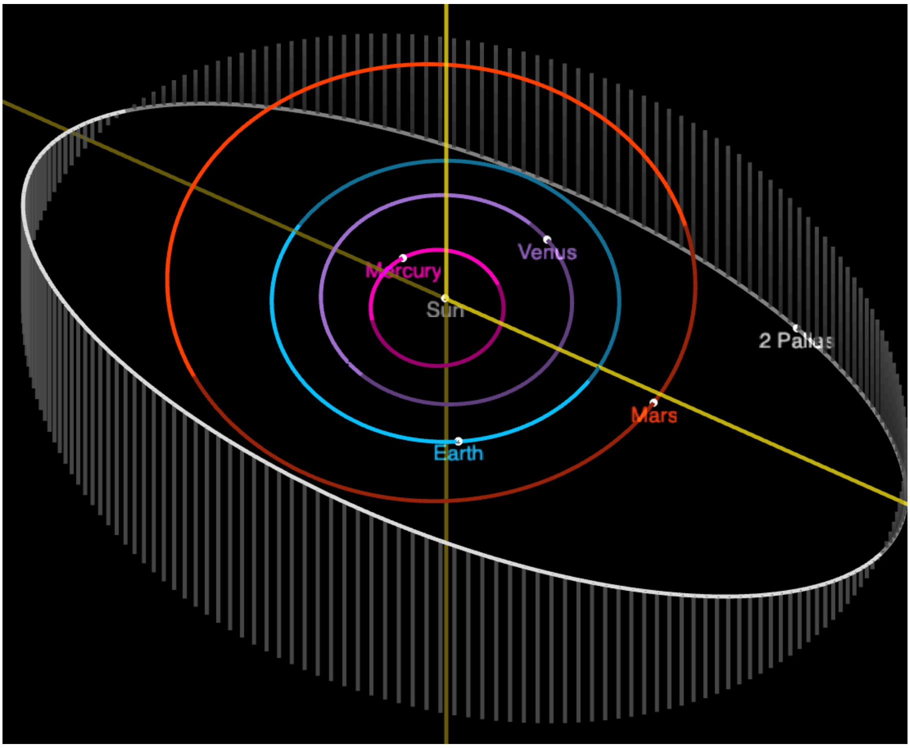

FIGURE 10. 3-dimensional diagram from the NASA-JPL Small Body Browser showing the orbit of 2 Pallas and the inner planets in the ecliptic.
https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=Pallas&view=VOP

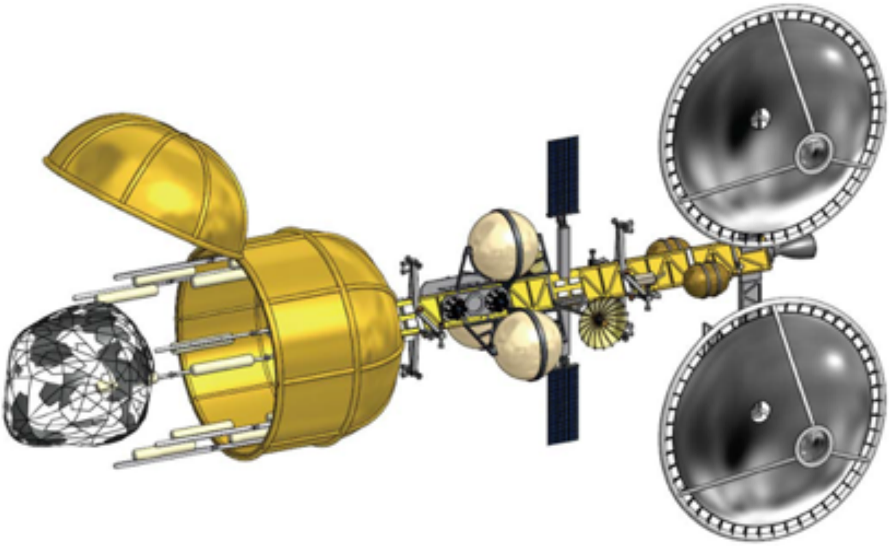

FIGURE 11. Robotic Asteroid Prospector spacecraft design shown capturing a small asteroid, showing the truss, engine, fuel tanks, water cargo tanks, outriggers, solar parabolic concentrators, and alpha joint configuration. CAD drawing by Phillip Chu, Honeybee Robotics, as subcontractor to Astrotecture®.

11. Mars Missions

This section focuses on the time and space integration issues. In organizing a mission from Earth to Mars, time and location in space share critical importance. On a Mars mission, *where you start* and *when you start* become almost synonymous. This unity becomes apparent when examining the two main trajectory options for sending a spacecraft from Earth to Mars. These two main options are the Opposition Class or “short stay” mission versus the Conjunction Class or “long stay” mission.

There have been a great many architectural design projects for Mars surface habitats, bases, settlements, and even cities. Unfortunately, if any of them have considered the full implications of the space and time interaction**.** I include my own lunar and Mars, base designs such as “First Mars Outpost Habitation Strategy”(Cohen, 1996) in this assertion. This necessary integration may not seem like a big deal if we assume that everything will always go as planned on the way to Mars, after arrival on Mars, and in departing Mars to return to Earth. As either a government or a corporate program, what could possibly *dare* to go wrong?

The next diagrams in FIGURES 12a and 12b demonstrate how differences in perspective and in perception can sow the seeds of fundamental disagreements about the physics, navigation, and spacetime of anything so simple as a human Mars Mission.

The two trajectory diagrams begin to explain the differences, but first, in both figures the view is from the “north” or “top-down” toward the ecliptic plane. From this vantage point, all the planets revolve about the Sun in a counter-clockwise direction. I chose these diagrams from among many by NASA to show specific dates upon which the major departures and arrivals would have occurred (in 2014). In the case of both mission classes, the launch windows from Earth to Mars and return last about 60 Earth days, and the departure windows open only every Earth-Mars Synodic Period (approximately 26 Earth months).

Now for the differences:

An Opposition Class mission such as the one shown in FIGURE 12a affords the short stay gives the crew about 30 days on the Mars surface, depending on the particular departure window in the series of 26-month synodic periods between the Earth and Mars. Overall “short stay” mission duration would be about 545 Earth Days. This value gives a ratio of 30/545 = 0.055 days on the Mars surface per day in space.

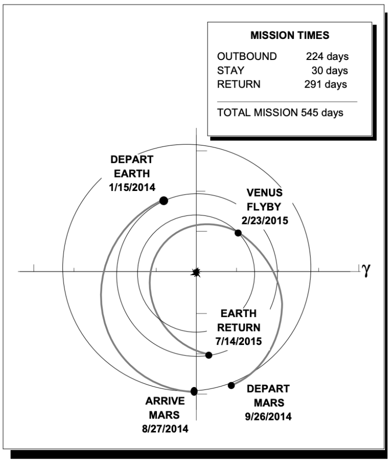

FIGURE 12a. Opposition Class “long stay” mission to Mars., (Hoffman, Kaplan; 1997; p. 3-37) Credit: NASA.

http://spacearchitect.org/pubs/NASA-SP-6107.pdf

A Conjunction Class Mission affords the long stay time of about 500 days on the Mars surface, depending on the particular departure window in the series of 26-month (780 days) synodic periods between the Earth and Mars. Overall “long stay” mission duration would be about 900 Earth. This value gives a ratio of 500/900 = 0.555 days on the Mars surface per day in space.

This pair of diagrams “stacks the deck” in favor of the Conjunction Class trajectory. It was not enough for the team leaders that all the evidence supported the “long-stay” mission and that we reached a rare consensus to recommend the conjunction class. They inserted this bias into the documentation. They show almost the same Earth Departure date for both trajectories, but the Opposition Class requires a much longer return leg involving a Venus flyby to return to Earth with the least expenditure of Δv.[8] This departure date for the Opposition Class is unnecessarily disadvantageous, but that’s how they played the game in Houston in those days.

Realistically, the optimal Opposition Class mission would depart Earth on a different launch window than the rival trajectory. Because of this type of example that scientific and engineering diagrams, findings, and results can be presented in a biased way, it is vital for Space Architects to become critical consumers

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[8] For a given propellant mass constraint, which relates to total propulsive Δv, mission expense is a function of space, time, gravity and gravity losses, and most of all, *mass.*

of the relevant scientific and technical literature.

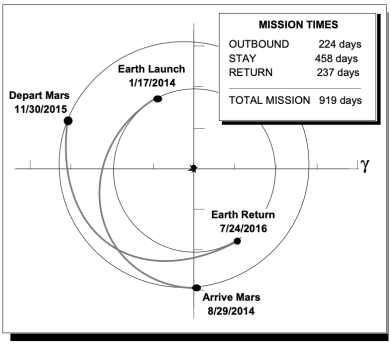

FIGURE 12b. Conjunction Class "long stay" mission to Mars. (Hoffman, Kaplan; 1997; p. 3-37) Credit: NASA. http://spacearchitect.org/pubs/NASA-SP-6107.pdf

This next comparison of Opposition and Conjunction Class trajectories in FIGURES 13a and 13b shows a fair comparison them in probably their most optimal launch windows touching the current decade. The second pair of orbital trajectory diagrams show this different rendering of the Opposition Class Mission. This comparison of the two pairs of diagrams demonstrate how even astronautical data can be slanted or bend the reality of the physics. That is why it is essential for Space Architects to be literate in these fields and to comprehend the forces that will influence their designs, often in ways that may drive success or failure.

In this second pair of Mars trajectory diagrams the Conjunction Class mission departs the Earth about 90° further counter-clockwise than the Opposition Class Mission. Think of the Opposition Class Mission as the Earth and Mars starting on near-opposite) sides of the Sun. Certainly, the spacecraft arrives at Mars more than 180° from where it departed Earth, arriving on the opposite side of the Sun.[9]

In this pair of examples, the ratio of time on the surface occurs in the same way as the previous pair of diagrams. For the Opposition Class, the ratio of 40 days on the surface/661 days in space = 0.060 days on the surface for each day in space. For the Conjunction Class, the ratio of 545/905 = 0.602 days on the surface for each day in space. Both these results are better than the results from the first pair and they maintain the 10:1 ratio of surface time on a long stay to surface time on a short stay.

I served as a "contributing author" on the first NASA Mars Design Reference Mission "MDRM 1.0" (Kaplan, Hoffman; 1997; pp. 3-37 to 3-42). Perhaps the most definitive result of the MDRM 1.0 — and never altered in subsequent serious study iterations — was the selection of the Conjunction Class trajectory for the first human mission to Mars. This result was based on the recognition that the only safe and realistic mission design is to conduct the 500 to 600 days on the surface Conjunction Class mission instead of the 30 days on the surface Opposition Class Mission.

In fact, that decision marked a rare unanimity and consensus on our team. One of many reasons was that in the event of a failure to be able to launch the crew in the Descent-Ascent Vehicle (DAV) safely back to Mars orbit, the necessary fail-safe would be to "abort to the surface." To make the failsafe viable, that would mean sending an additional 600-day surface habitat in addition to the 30- day Opposition Class habitat.

The most immediate effect of time and space on Space Architecture involves the distance from the safety of the Earth and the amount of time required to travel to a lunar, orbital, or planetary destination and then the time to return safely to the Earth. In addition, to travel to Mars, there are limited departure windows to launch from the Earth that occur every Earth-Mars synodic period of approximately 26 months (780 days) Similarly, the departure window to return from Mars occurs only after a long interval of 500 to 600 Mars sols (24-hour, 40-minute day night cycles). This interval dictates that the design of such a human Mars mission must support the crew on Mars for those 500 to 600 days, with further fallback and safety provisions in case the crew are not able to launch at the planned departure window.

Also, the crew and operations support on Earth must contend with the communications two-way time lag that will range from about 16 minutes when Mars is closest to the Earth to about 46 minutes when it is (almost) farthest from the Earth. When Mars is actually farthest from the Earth it is on the other side of the Sun; there are no communications because the Sun blocks all transmissions. Under these types of constraints and imperatives, the influence of time and space will cause a far greater impact

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[9] The two mission classes derive their names from the relative positions of Earth, Mars, and the Sun at the mission midpoints. The Opposition Class mission midpoint occurs when Mars is near opposition to the Sun as seen from Earth; the Conjunction Class mission midpoint occurs when Mars is near conjunction with the Sun as seen from Earth.

on humans on space missions than they do on Earth.

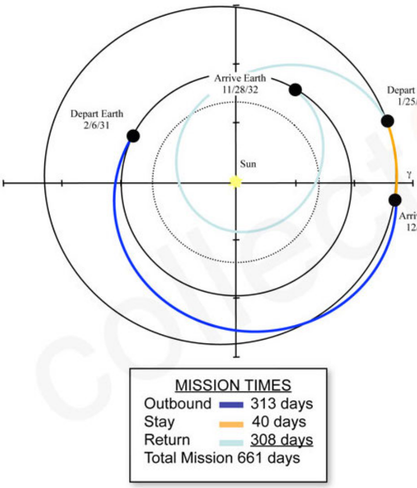

FIGURE 13a. Opposition Class "short stay" Mission to Mars

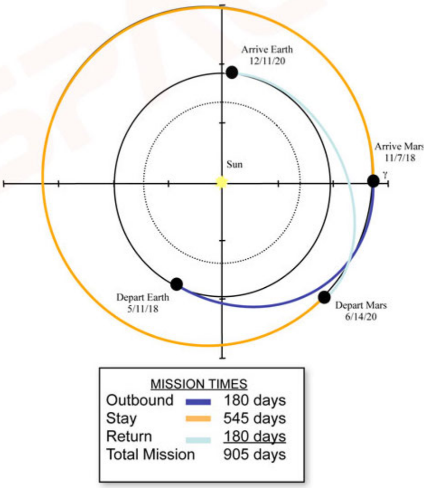

FIGURE 13b. Conjunction Class "long stay" Mission to Mars

Credit: NASA, courtesy of Collectspace.com.

12. Space, Volume, and Mission Duration

One of the leading questions that challenged NASA human factors engineers, mission planners, and psychologists was: How much space cabin volume does the crew need to conduct a healthy, safe, and successful mission? Available pressurized volume constitutes one of the leading challenges of Space Architecture design for habitability. Crew requirements and tasks can vary substantially from one mission to another and from one spacecraft to another. Researchers suggested multiple independent variables including number of crew, level of crew performance required, spacecraft mass, and mission duration, to name a few.

In 1963, Celentano, Amorelli, and Freeman[10] at North American Aviation in Downey, California, (where they became members of the team that built the Apollo Command module and the Space Shuttle as Rockwell International) proposed *mission duration as* the crucial independent variable. They presented their conjecture as a set of curves with varying levels of being "tolerable" or "optimal." FIGURE 14 shows an imitation of the Celentano conjecture. But the space age was just in its infancy, particularly in respect to human spaceflight. So, the debate about the relationship between among crew number, cabin volume, and mission duration only intensified.

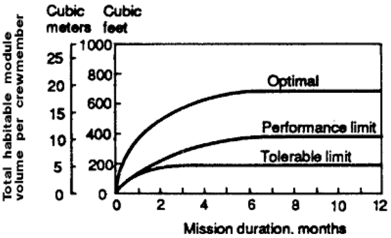

FIGURE 14. Marton, Rudek, Miller, Norman (1971) imitation of Celentano, Amorelli, and Freedman's curves, as published in NASA Std. 3000, Man-System Integration Standard (MSIS), Figure 8.6.2.1-1. Guideline for determination of total habitable volume per person in the space module.

In the period 2004 to 2010, NASA and its contractors were preparing for the Constellation lunar program. Questions about the necessary volume arose again with respect to the Orion Crew Exploration Vehicle, the Altair Lunar Lander, and lunar surface habitats. By this time, forty years after Celentano, Amorelli, and Freeman, we had accrued a much larger data set consisting of about 250 human space missions.

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[10] In 1984 I met Amorelli and Freeman at the Rockwell Downey plant (Celentano had retired) where we discussed their famous conjecture and how it might be possible to research and improve upon it.

Compiling and using this data, the Northrop Grumman team developed a strategy that would lead to proposing a design and size for the Altair Lunar Lander.

We published these results in 2008. There was an abundance of "common sense," "gut feelings," and received wisdom about this vital question, but they only added up to a severe poverty of data in any organized format. Many people throughout the human spaceflight community had produced their own pet versions of the Celentano Curve. One such example is Marton, Rudek, Miller, Norman (1971) in FIGURE 14, who basically just copied the Celentano curve uncritically and without giving credit. The main purpose of our Northrop Grumman exercise was to establish what are the facts about pressurized spacecraft volume, crew size, and mission duration.

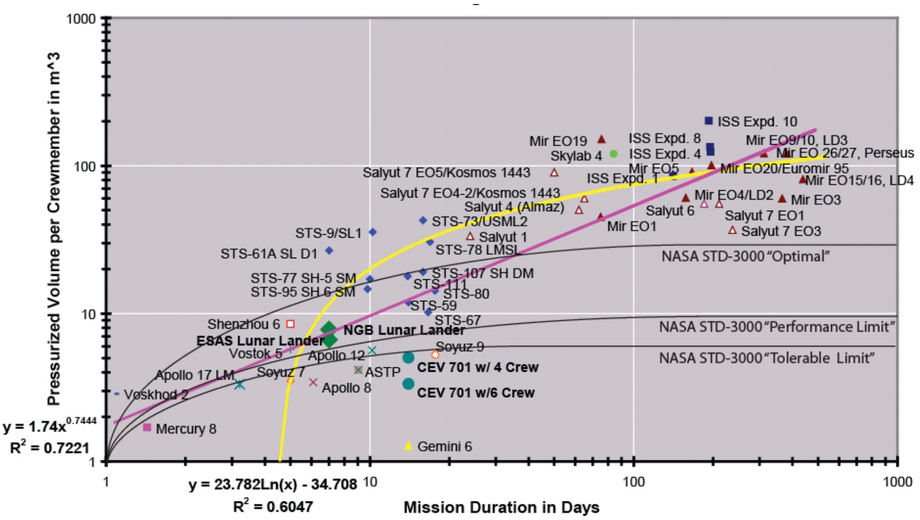

FIGURE 15. Pressurized volume per crew member versus mission duration: Maxima for mission durations for every crew size in each spacecraft configuration (Cohen, 2008, p. 20).

In Testing the Celentano Curve, I constructed the curve based on data from over 250 spaceflights. The results of Testing the Celentano Curve (Cohen, 2008) showed that Celentano, Amorelli, and Freeman's conjecture about the curve rising and then leveling out held up to scrutiny, at least when plotted as a logarithmic curve as shown in FIGURE 15. However, two other prominent features of Celentano failed to find any supporting evidence. There is no evidence WHATSOEVER of the three hierarchical curves of tolerable, performance, and optimal levels of volume to accommodate the crew. Neither is there any support for the arbitrary notion that all three curves pass through the origin (X=0, Y=0).

This plot of pressurized volume per crew member versus mission duration displays the crewed spaceflights with the largest crew or the largest volume for that class of vehicle. Their pressurized volume is plotted against their mission duration. The light (yellow) logarithmic curve confirms the Celentano, Amorelli, and Freedman conjecture that the curve rises and then levels off as the mission duration lengthens. The darker (purple) straight line power curve shows the same data but with a slightly different distribution. Neither curve passes through the origin, 0,0. This plot from Testing the Celentano Curve has been reproduced widely in articles, books, and dissertations, much the same as happened to the original conjecture. Hopefully, Space Architects will learn to take a critical view of conjectures that do or do not stand on empirical data.

13. Conclusion

Just as the sequence of the text is associative, so is this conclusion — perhaps even more nonlinear. The first finding in the conclusion is that Time and Space influence our lives and daily routines to a much greater extent than most people realize. Yet, in space travel, these influences become far more acute, and potentially more hazardous to the crew's health and lives.

Second, Space Architects can play their full role to protect the health and safety of people in space only if they comprehend that environment and the forces that shape it, much in the same manner that James Marston Fitch[11] (1947, 1999) advocates. Unlike on the Earth where the ground on which architects build is relatively static — even with earthquakes — the space environment is much more dynamic and influenced in uncontrollable ways by the absence of an atmosphere, reduced or microgravity, and the motion of spacecraft and celestial bodies through spacetime.

The third finding is that Space Architects need a solid foundation in these influences that derive from astrodynamics. celestial motions, physics, and spacetime. Without this understanding, astronautics would be impossible. So, would be Space Architecture that meets the professional standard of care to protect the health and safety of the people.

Fourth and finally, Space Architects must learn to become generalists in the external imperatives and constraints of humans living and working in space. These forces and the design solutions to them determine *what is* and *what is not* possible in designing a space mission and the spacecraft or surface habitat to perform that mission.

In managing a building project on Earth, architects coordinate all the allied disciplines as the design integrator. Why shouldn't architects perform the same role in space? Why should it be expected that Space Architects can be relegated to making shells in which engineers pack their subsystems. Why isn't the Space Architect taking charge of these distributed systems both internally and externally to the habitat?

To sum up: Space may not prove to be the "Final Frontier" as envisioned during the Apollo era; hopefully it won't be. There may be further frontiers both internally and externally. However, Space is the most immediate and most vast frontier. Understood within all the infinite potentialities of spacetime, it offers the greatest challenges to all the architectural, design, engineering, and construction professions.

Acknowledgement

I would like to thank Tom Gangale for his careful reading of the draft of this paper and his generous, concise comments, some of which endure as footnotes here.

References

Apian, Peter (1524). Cosmographica, Gemma Frisius expanded edition (1545), Antwerp & Basel: Georgio Bontio(?). Also, the (1574) edition, Köln: Arnold Birckmann Erben. Swetz, Frank [Webpage Editor] (2013, August). "Mathematical Treasure: Peter Apian's Cosmographica." https://www.maa.org/press/periodicals/convergence/mathematical-treasure-peter-apian-s-cosmographia, accessed 24 June 2022.

Berthoud, Ferdinand (1767). *The principles of Mr Harrison's time-keeper*, London, Great Britain: Commissioners of Longitude. Printed by W. Richardson and S. Clark and sold by J. Nourse. https://archive.org/details/principlesmrhar00unkngoog, accessed 5 July 2022.

Celentano, J. T.; Amorelli, D.; Freeman, G. G. (1963 May). Establishing a Habitability Index for Space Stations and Planetary Bases (AIAA 63-139). AIAA/ASMA Manned Space Laboratory Conference, Los Angeles, California, USA, 2 May 1963. New York, New York, USA: American Institute of Aeronautics and Astronautics. http://spacearchitect.org/pubs/AIAA-63-139.pdf.

Cohen, Marc M. (1996). First Mars Outpost Habitation Strategy (AAS 95-491). In C. Stoker, C. Emmart (Eds.), *Strategies for Mars: A Guide to Human Exploration* (American Astronautical Society, Science and Technology Series, Vol. 86, p. 465-512). San Diego, California, USA: Univelt, Inc.

Cohen, Marc M. (2009 April). Testing the Celentano Curve: An Empirical Survey of Predictions for Human Spacecraft Pressurized Volume (SAE 2008-01-2027). 38th International Conference on Environmental Systems (ICES), San Francisco, California, USA, 30 June - 2 July 2008. In, *SAE International Journal of Aerospace* (vol. 1, no. 1, p. 107-142). Warrendale, Pennsylvania, USA: Society of Automotive Engineers. http://www.astrotecture.com/Human_System_Integration_files/SAE-2008-01-2027%20%282%29.pdf

Cohen, Marc M.; James, Warren W.; Zacny, Kris; Craft, Jack; Chu, Philip; Blair, Brad (2013 December 12). Robotic Asteroid Prospector (RAP). NASA Innovative and Advanced Concepts (NIAC), contract NNX12AR04G. Palo Alto, California, USA: Astrotecture.

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[11] Fitch was a professor at the Columbia University Graduate School of Architecture, Planning, and Preservation while I was a M.Arch student there, but he was committed to developing the Historical Preservation program. I attended a couple of his talks.

http://spacearchitect.org/pubs/NIAC-NNX12AR04G-20131212.pdf

Copernicus, Nicholas (1543). De Revolutionibus Orbium Coelestium [On the Revolutions of the Heavenly Spheres], Norimbergae: apud Ioh. Petreium, [Nuremburg: Petreium].

Fitch, James Marston (1947, updated 1999). American Building: The Environmental Forces that Shape It, New York, NY: Houghton Mifflin.

Fuller, R. Buckminster (1969). Operating Manual for Spaceship Earth. Carbondale, IL, USA: Southern Illinois University Press.

Fuller, R. Buckminster; Marks, Robert W. (Ed) (1965). Ideas and Integrities: A Spontaneous Autobiographical Disclosure, Englewood Cliffs, NJ: Prentice-Hall, Inc.

Galilei, Galileo (1953). Dialogue on the Great World Systems in the Salusbury Translation (1661), Revised, Annotated, and with an Introduction by Giorgio de Santillana, Chicago, IL: University of Chicago Press. https://archive.org/details/dialogueongreatw0000gali_o8o6/page/n7/mode/2up, retrieved June 26, 2022 [but I read it in high school, 1969].

Hoffman, Stephen J.; Kaplan, David L. [Eds.] (1997 July). Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team (NASA SP-6107). Houston, Texas, USA: Johnson Space Center, NASA. http://spacearchitect.org/pubs/NASA-SP-6107.pdf

Jewish Publication Society (2006). The Contemporary Torah. https://www.sefaria.org/Exodus.12.2?lang=bi&aliyot=0 retrieved 09 May 2022.

Johnson Space Center (1995 July). Man-Systems Integration Standards (NASA STD-3000, Revision B). Houston, TX: NASA. https://msis.jsc.nasa.gov/

Linceo, Galileo Galilei (1632). Dialogo sopra I due massimi sistemi del mondo, Fiorenza, Italia: Elzevir.

Marton, T.; Rudek, F. P.; Miller, R. A.; Norman, D. G. (1971, October). Handbook of Human Engineering: Design Data for Reduced Gravity Conditions, NASA CR-1726. Washington, DC: NASA. https://ntrs.nasa.gov/search?q=Marton, T.; Rudek, F. P.; Miller, R. A.; Norman, D. G.

Overduin, James (2007) Einstein's Spacetime, Gravity Probe B: Testing Einstein's Universe, Palo Alto, California USA: Stanford University. https://einstein.stanford.edu/SPACETIME/spacetime2.html

Shakespeare, William (1600). Mid-Summer Night's Dream, London: Quarto. http://shakespeare-online.com/plays/mids_1_1.html

Stanford Encyclopedia of Philosophy (2020). Philolaus. https://plato.stanford.edu/entries/philolaus retrieved 30 June 2022.