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Orbit Dynamics and Habitability Considerations for a Space Hotel with Artificial Gravity

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ABSTRACT

A space hotel with all the comforts of home including artificial gravity equal to that at the surface of Earth is analyzed and architected. Guests would undertake safaris on smaller spacecraft to enjoy microgravity activities but return to the hotel for dining, sleeping, and attending to other personal needs. The optimal spin characteristics of the hotel are shown to require a specific range of altitude and to favor an equatorial orbit. Implications of the orbital hotel for the future colonization of space are presented at the conclusion.

I. INTRODUCTION

This paper analyzes the means by which a space hotel would be maintained in low Earth orbit (LEO) through the application of satellite orbit dynamics with the goals of maximizing human safety, health and comfort. A successful venture in this arena would point the way to the future colonization of space. In the nearer term it would provide the means to generate considerable revenue for Earth-based private corporations, also to stimulate popular interest to promote the sustainable exploitation of space. However, this paper is entirely technical and does not make a business case for a space hotel.

Discussion begins with historical background to set this study in perspective and to reveal gaps in current knowledge. Background is also provided to define and explain the concept of artificial gravity and to discuss why it is central to this discussion. Orbit dynamics is applied to constrain the optimal trajectory for a space hotel to maximize safety and health factors, both for the guests and the hotel workers. National prestige and related considerations were not permitted to dictate the design. At the conclusion the implications for the future colonization of space are presented. A mathematical appendix follows to provide the background to the analysis.

II. DEVELOPMENTS FROM HISTORICAL AND TECHNICAL BACKGROUND

A. SPACE HOTEL CONCEPTS

Space hotels have been discussed for many years and entrepreneurs such as Robert Bigelow have supported development of this concept. The International Space Station (ISS) has been visited by 7 private citizens, one of whom was aboard on two separate occasions. These visits were funded by the individuals themselves so they serve as early examples of the space tourist concept. A Hilton Hotel was depicted aboard a wheel-like rotating space station in the 1968 film *2001: A Space Odyssey*. Thus we have two concepts of space hotels known to the general public: one with a microgravity environment and one with an artificial gravity environment.

B. ARTIFICIAL GRAVITY

Space stations that rotate to generate artificial gravity have been of interest ever since the early work of Konstantin Tsiolkovsky[1], Hermann Potočnik[2] (pen name: Hermann Noordung) and Hermann Oberth. In the 1920s Oberth[3] published the concept of generating artificial gravity by connecting two orbiting rockets with a cable and rotating them about each other: the first known description of the architecture assumed in this paper (Figure 1).

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In the early 1950s Wernher von Braun[4] and his colleagues proposed the establishment of a wheel-shaped rotating station at an altitude of 1,075 miles (1,730 km) above Earth.

The urgency of the ‘moon race’ initiated by President John F. Kennedy in 1961 turned national attention away from space station development. After the race was won a succession of space stations were launched over a span of decades, however no space station which rotates to generate artificial gravity has ever been launched. The concept was abandoned in 1963 after studies at NASA-Langley Research Center concluded that artificial gravity was better suited when large crews were expected to live in comfort[5] as opposed to the small crews actually being sent into space.

In 1966 the Gemini 11 capsule was connected to its Agena docking target vehicle by a 100-foot (30 m) tether, then the capsule’s thrusters were fired to cause the two craft to revolve around each other with a 9-minute period (0.11 rpm). Thus Oberth’s concept was implemented. No gravity-like force was observed by the astronauts; but it was estimated that an object within the capsule would fall 3 inches in 10 seconds[6]. A space structure of this configuration consisting of two large nodes connected by a tether or lightweight truss in the form of a dumbbell is envisioned for the hotel in this paper (Figure 1). The orbital geometry for this configuration is displayed in Figure 2.

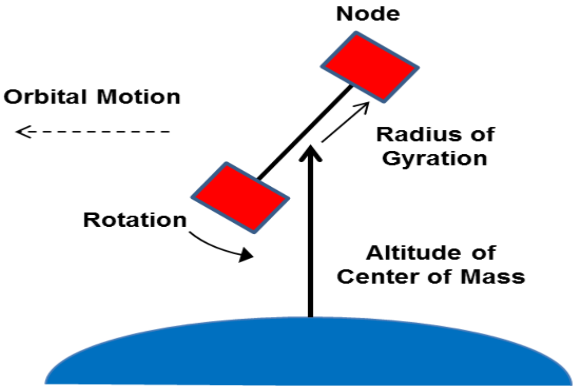

Figure 1. Hotel dumbbell architecture.

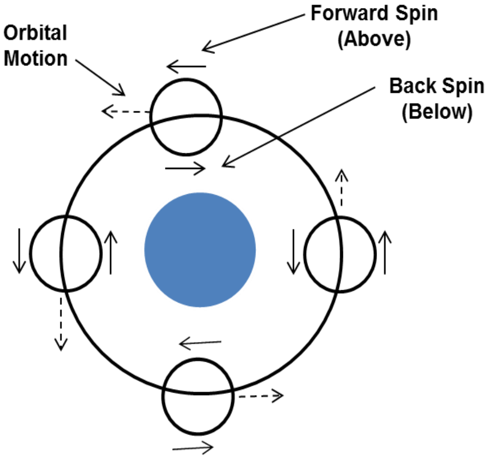

Figure 2. Orbital geometry with body rotation

C. MICROGRAVITY HEALTH AND HUMAN FACTORS

Human-occupied space capsules and stations have been operated on various missions for more than half a century, entirely in a microgravity environment. Considerable research has been performed involving laboratory animals and bacteria in both microgravity and artificial gravity environments in space. Humans have been found to experience a variety of unhealthy effects, including a deterioration of the major bones that support body weight and a calcium loss at a rate of 1.0% to 1.5% per month[7]. This release of calcium appears to cause astronauts to be at an elevated risk of developing kidney stones[8]. Individual new human cells form improper cytoskeletal structures as they grow[9] in microgravity, raising serious questions about viability of young people in space.

Space Adaptation Syndrome has proved a nuisance to astronauts for the first few days following launch[10]. Two hours per day of exercising to protect cosmonauts against the loss of muscle mass was proscribed for the Mir missions[11]. Returning to Earth after extended stays in microgravity has been found to require rehabilitation: after his 84-day visit to Skylab Gerald M. Carr reported[12] having to become re-accustomed to the weight of his head on top of his body, comparing it with a “watermelon”.

While humans and animals such as primates and rodents appear to suffer harmful effects in microgravity and have not been observed to reproduce and raise offspring, bacterial reproduction and growth has been found to proceed in an alarming direction. Salmonella bacteria have been found to undergo new gene expression and become more infectious[13], raising the possibility that microgravity habitations could become sources of new and deadlier strains of diseases, particularly if they are visited by many people on a casual basis. Bacterial strains observed in the Skylab 3 crew prior to launch were found in the Skylab 4 crew following their landing even though these particular strains were not observed in the Skylab 4 crew prior to liftoff[14]. Thus we have a documented case in which exposure to bacteria occurred in space.

D. CENTRIFUGE HEALTH AND HUMAN FACTORS

Human and animal research with centrifuges on the surface of Earth has been performed for many years. Rotation rates in excess of 1 rpm appear to have disorienting effects for humans. These include vomiting in the short term, however subjects have adapted to the rotating environment over longer durations[15]. Experiments with rotating rooms indicate that nearly all subjects could accommodate[16] 1 rpm although head movement still induced discomfort[17] even at this modest rotation rate.

The means to design the hotel to minimize this effect, which appears to be due to precession, are discussed in part III, section C below. This and other potentially bothersome phenomena are summarized in the Table.

Table. Summary of effects involving artificial gravity due to rotation and counter-measures.
The most serious issue is listed at the head and the others are listed in descending order of severity.

Effect	Source	Counter-measures (listed in order of ease of implementation)
Precession	Head rotation	Align beds with spin axis, Lower spin rate w/ larger gyration radius
Coriolis	Vertical motion	Lower spin rate with larger gyration radius
Gravity Level Change	Horizontal motion	Align runway w/ spin axis, Lower spin rate w/ larger gyration radius
Disorientation	Hotel rotation	No direct viewing of Earth from hotel, view Earth from safari craft
Gravity Gradient	Hotel rotation	Smaller gyration radius, however effect is very small

A number of experimental spacecraft launched by Russia have included centrifuges for research involving animals. Fish and turtles centrifuged at 1 g aboard Kosmos 782 in 1975 were found to be indistinguishable from their ground controls[18]. Continuous rotation which generates artificial gravity of 1 g at the feet of a rodent was observed to be sufficient to maintain normal growth[19].

Coriolis acceleration, familiar to many people from walking inwards or outwards on a merry-go-round and observing a tendency to drift to the right or the left, is an undesirable side effect of artificial gravity. This particular feature of artificial gravity is not a realistic representation of natural gravity because it is not present in the normal terrestrial environment. It can therefore be disorienting and confusing.

The Coriolis acceleration can be ameliorated by simply increasing the radius of gyration of the habitat (defined in Figure 1) for a constant level of acceleration. Figure 3 presents the results: Coriolis acceleration over the average adult male human height (1.8 m) in the range of the maximum acceleration of an ordinary elevator[20] (0.05 g) can be obtained if the radius of gyration is about 1000 m for 1 g artificial gravity. Figure 3 also shows this corresponds to a spin rate of about 1 rpm. This figure also shows that multiple-rpm spin rates involve far higher Coriolis accelerations and are therefore unacceptable for a space hotel with 1 g artificial gravity.

Figure 4 shows that a linear spin speed on the order of 100 m/s is required for a radius of gyration of 1000 m with 1 g artificial gravity. A comparison of Figures 3 and 4 shows that larger radii of gyration involve higher linear spin speeds but lower angular rates.

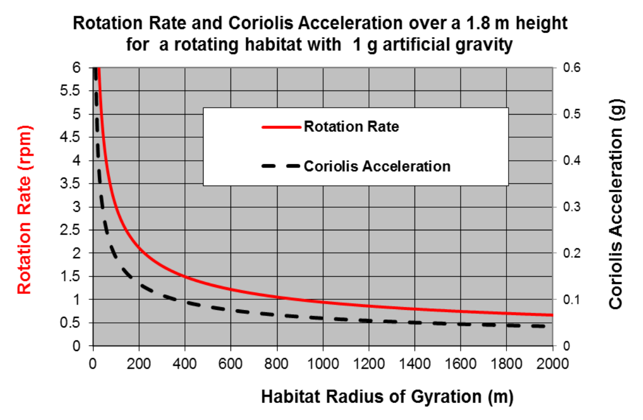

Figure 3. Habitat rotation rate and Coriolis Acceleration.

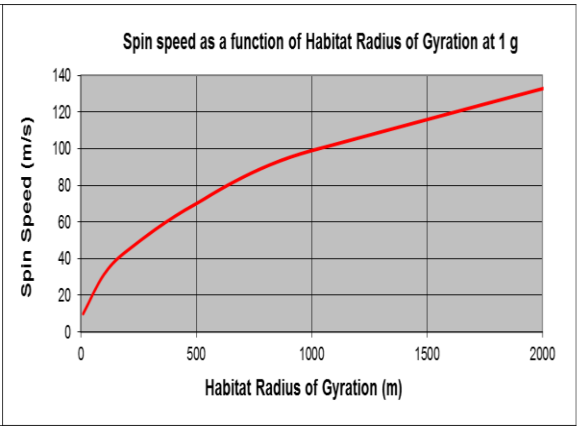

Figure 4. Linear Spin speed as a function of radius

E. ORBITAL ENVIRONMENT

Human space flight, except for trips to the moon and to the modest apogee altitude of about 1400 km briefly achieved during the Gemini 11 mission, has been confined to low Earth orbit to avoid the inner Van Allen radiation belt and to facilitate travel from and back to Earth. The ISS operates between 300 km and 400 km, thus avoiding the danger of atmospheric drag and re-entry from a lower orbit. For the space hotel the circular orbit heritage from ISS and previous stations is carried over to simplify operations.

However, elliptical orbits for the habitat must be considered to allow for conditions following a break in the structure, either due to a meteor or debris strike or deliberately induced to prevent the spread of an uncontrollable fire by eliminating the convective flow of air supported by a 1 g environment. A minimum perigee height of 200 km and a maximum apogee height of 1200 km were imposed to limit air drag at perigee and to protect against radiation effects at apogee in a post-break orbit. This would permit the habitat to be retrieved following evacuation of the guests and non-essential hotel staff by escape craft. Figures 5 and 6 apply these constraints.

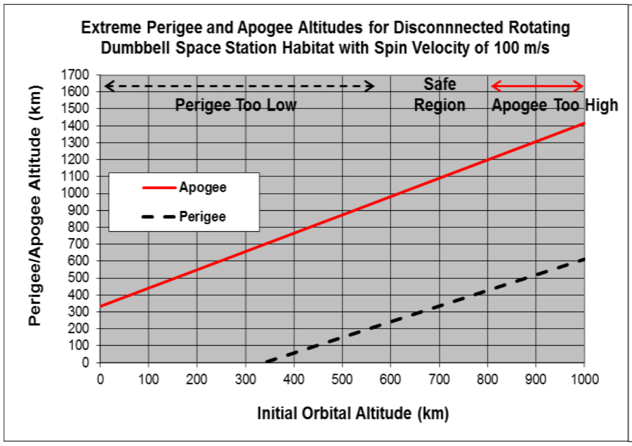

Figure 5. Safe Region for Hotel is at 600-800 km

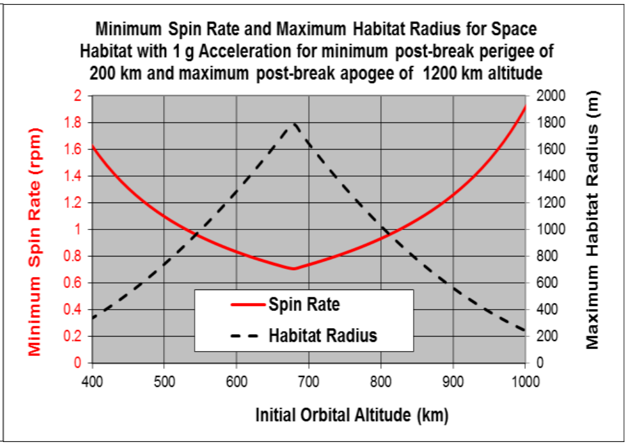

Figure 6. 1 rpm rate and 900-1000 m radius are optimal.

Figure 5 assumes a linear spin speed of 100 m/s. Adding to or subtracting this speed from circular orbit speed yields the maximum apogee and minimum perigee height that could result from a break in the structure. Figure 6 solves for habitat spin rate and radius of gyration from the imposed maximum apogee and minimum perigee, indicating that desirable rotation rates of 0.5 rpm or below to avoid discomfort from head movement are unattainable for LEO artificial gravity faciltities operating at the 1 g level. Therefore, rates significantly below 1 rpm as well as rates above that level have been ruled out for the space hotel.

F. APPARENT GRAVITY MODIFICATION WHILE WALKING

The approximately 100 m/s linear spin speed of the hotel habitat is vastly greater than any speed that a guest could achieve, thus minimizing the change in apparent artificial gravity level due to personal motion. A fast walk involves a speed of 1.5 m/s, or about 1.5% of linear spin speed. Artificial gravity depends upon the square of total linear spin speed so it would be increased or decreased by about 2.3% or 0.023 g depending upon whether the walker was moving in the direction of spin or in the opposite direction. The total variation is somewhat less than 0.05 g, the acceleration level for an ordinary elevator on Earth, so no problems are expected. For avid sprinters a runway parallel to the spin axis could be provided since motion parallel to the axis does not affect linear spin speed.

G. GRAVITY GRADIENT EFFECTS

Gravity gradient, or differential gravitation, is a force arising from the finite extent of a structure with a significant length along the radius from the center of Earth. When the rotation of the dumbbell structure of the hotel (see Figure 1) causes the line connecting the structural nodes to be parallel to the radius vector to the hotel center of mass from the center of Earth, the inner node is attracted more strongly by terrestrial gravity than the outer node. This section will show that no significant effects are generated.

As Figure 1 indicates, the hotel habitat node altitude above the surface of Earth varies during the spin of the rotating structure over a range of altitude equal to its diameter of gyration. This will generate a minor increase to the level of artificial gravity experienced within the habitat of about 0.00025 g when the long axis of the structure is aligned with the radius vector, or every 30 seconds for a 1 rpm rotation rate. This is about 0.5% of the maximum acceleration experienced in an elevator and would be below the threshold of noticeability.

The 0.025% increase in force on the habitat due to gravity gradient effects would add linearly to the tension in the cable or truss connecting the two nodes in the dumbbell. The connecting structure would be expected to stretch in proportion, adding 0.5 cm (0.2 inches) to its 2 km length, so the habitat would appear to move up and down one-fifth of an inch every 30 seconds. The departure or arrival of a craft transferring guests from Earth whose mass was 1% of the total mass of the habitat would make a larger difference in its position.

Gravity gradient effects augment the gravitational force on the entire hotel structure at intervals of about 30 seconds, necessitating a very slight increase of 0.15 mm/s in orbital velocity. This enables the centrifugal pseudo-force generated by orbital motion to balance both the simple Newtonian gravitational force plus the averaged gravity gradient force, assuming 600 km altitude and a 1000 m radius of gyration. This is a very small correction to the 7560 m/s orbital velocity and would be far smaller than the effects from the arrival and departure of transfer craft.

H. LAUNCH AND RETURN TO EARTH

Minimum transit time from Earth to the hotel and back to Earth are desirable to mitigate Space Adaptation Syndrome. This simplifies transit spacecraft design since it does not have to serve as a recreational vehicle but merely as a bus. Exposure to microgravity during this phase would last no more than two hours, which would be comparable to that experienced during a "microgravity safari" undertaken during a vacation at the hotel, as will be discussed in part III, section B.

Launch and landing opportunities for flights to and from the hotel are maximized to facilitate economical operation. A missed launch opportunity due to equipment, weather or other problems would not be an issue if it could be made up within 2 hours. The ability to liftoff throughout the day and night from a given launch site would be advantageous to maintain a regular traffic flow, also to prevent large numbers of passengers from having to be accommodated for extended periods at the launch facilities.

Adoption of an equatorial orbit minimizes transit time to the hotel and maximizes the number of launch opportunities per day. Furthermore, it permits the spin plane of the rotating hotel structure to always remain parallel to its orbit plane. In non-equatorial orbits with inclinations other than 90° nodal regression causes the orbit plane to rotate in inertial space while the spin plane of a rotating body tends to retain its initial orientation.

Transit time to the hotel is minimized for an equatorial orbit since no orbital plane change is required if an equatorial launch site is used. Transit times to Mir and other space stations are as long as two days in some cases and are reduced to about six hours at best. Equatorial orbit also eliminates the need for very short launch windows so the launch site lies near the orbital plane at liftoff since it is permanently in the orbital plane. Opportunities to land back at the launch site or at one of several emergency sites on the equator in the event of an evacuation are also maximized.

The number of opportunities per day for launch is maximized by having the launch site lie in the orbit plane. Each time the hotel makes a synodic revolution around the Earth, or transits the entire range of terrestrial longitude, there is a launch opportunity at a given site. For a 600-km altitude circular orbit the synodic period is 103.7 minutes and for an 800-km orbit the synodic period would be 108.5 minutes. This provides more than 13 launch opportunities per day as opposed to a maximum of one to two for a launch site at significant latitude into an inclined orbit[21].

Figure 7 displays the orbital geometry for transit to the space hotel and Figure 8 applies this information to generate constraints on the duration of the launch window. The spacecraft loiters in a phasing orbit between launch and injection into the elliptical transfer orbit to the hotel for a variable duration to accommodate launch at all times within the window. The altitude of the phasing orbit, 242.5 km, is set so that the transfer orbit apogee speed will be 100 m/s less than the speed for a circular orbit at 600 km, corresponding to the linear spin speed of the space hotel.

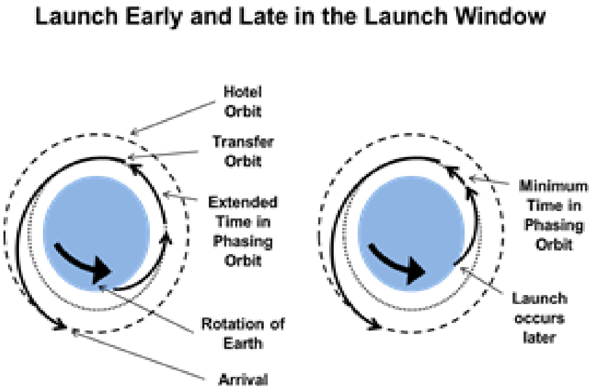

Figure 7. Orbital geometry for transit to the hotel

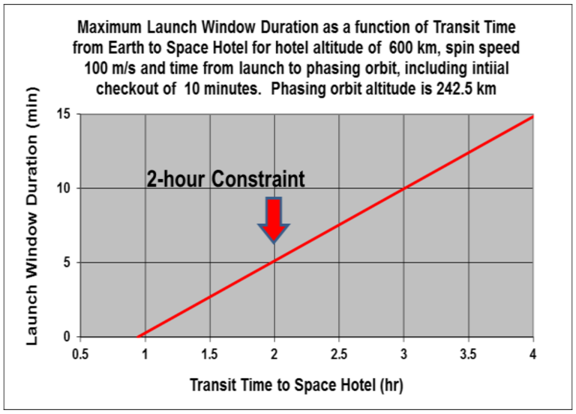

Figure 8. Launch window duration results

Imposing a ceiling of 2 hours for transit to the hotel, which is expected to minimize the effects of Space Adaptation Syndrome upon the guests, requires launch window duration to be no more than 5 minutes if hotel altitude is 600 km (Figure 8). With more than 13 opportunities daily, the total time per day over which a launch could be achieved would exceed one hour.

More detail on vehicle arrival at the hotel is presented in part III, section B below. This includes maneuver considerations. Details of the effects of vehicle arrival and departure upon the space hotel are not covered in this paper. However, it is assumed that any craft visiting the hotel has a mass no greater than 1% of the total hotel mass.

Launch vehicle capability is maximized by the use of an equatorial site since the entire equatorial rotational speed of the Earth is available to assist the vehicle to achieve orbital velocity. SeaLaunch uses a floating platform which is transported to the equator at a position south of Hawaii to maximize its payload mass capability. Land-based equatorial sites include Natal, Brazil and the San Marco platform off the coast of Kenya.

This strategy requires an equatorial launch and landing site, which of course would lie outside of the territories of the principal spacefaring nations and would not be of interest for national political, strategic or prestige reasons. Therefore, just as in the development of the SeaLaunch commercial business, economic justification would be required.

Development of Brazilian and Kenyan sites for space hotel launches would be appropriate for tourists hailing from the Americas, Europe, Africa or the Mideast, while a Far Eastern site could be developed to serve East Asian customers. These sites are all indicated in the map in Figure 9. Note that a considerable number of additional sites might be made available for a contingency landing in the event of an aborted ascent, or if the vehicle were unable to dock with the hotel.

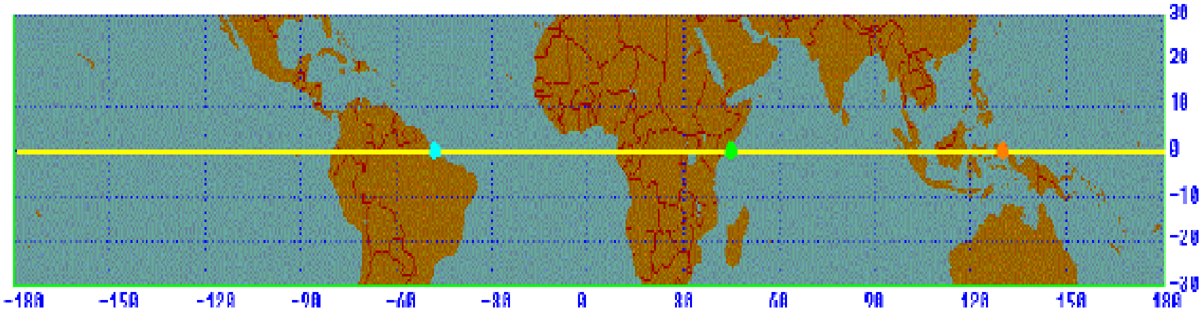

Figure 9. Map of Low Latitude Region of Earth with Space Hotel ground track and candidate launch sites

It is expected that all hotel guests would desire to remain on their own home time while visiting the space hotel to avoid disorienting “jet lag”. This would also facilitate observation of their home region of the world from space at a local time when it experiences daylight.

The detailed design and operational characteristics of the vehicles used to transfer passengers to and from the space hotel are beyond the scope of this paper. However, it is clear they would not require crossrange[22] capability like the U.S. Space Transportation System (STS) shuttle since all flights would occur within the equatorial plane. Furthermore high crosswinds are unlikely during landing in the doldrums region at equatorial latitude. A simple capsule configuration for carrying passengers would probably suffice. All launches would be in the same due east direction so a fixed catapult system could provide the initial impetus at liftoff.

III. SPACE HOTEL CONSIDERATIONS

A. HOTEL STAFF

Along with room temperature and a breathable atmosphere, artificial gravity would be an aspect of the terrestrial environment exported to space to maximize human safety, health, comfort and working conditions. While maximizing hospitality for the guests, the artificial gravity would permit the hotel staff to perform all of their tasks with maximum efficiency and minimum health risk.

The hotel staff is not assumed to include trained astronauts. It would perform labor only in a 1 g “shirt sleeve” environment using ordinary equipment such as brushes and sponges, mops and brooms, vacuum cleaners, washer/dryers (front-loading so these units can be installed with their rotating parts aligned with the spin axis of the hotel) and dishwashers. Like hotel workers and unlike flight attendants the housekeeping staff would not be responsible for directly assisting the guests, instead they would focus on keeping the hotel clean and sanitary.

A small but highly skilled astronaut-qualified core team would be trained to operate the habitat under all conditions to handle emergencies. Thus space hotel operations would resemble those aboard a cruise ship.

B. HOTEL GUEST ACTIVITIES

For a guest, a day at the hotel would begin with waking up from a comfortable night’s sleep and taking care of personal needs under normal terrestrial gravity. Sanitary conditions are thus optimized. A light breakfast would be recommended to make the day’s activities comfortable. Then the morning’s “microgravity safari” would begin.

Guests would board a craft suitable for free flight but not capable of operating in Earth’s atmosphere. The craft would cast off from the hotel at an instant when hotel rotation is carrying the habitat toward the zenith or vertically upward. This would inject the craft into an orbit with the same period as the hotel or about 97 minutes per revolution (rev) for a 600 km altitude. After one rev the craft would have traveled first through apogee, then perigee and returned to the space hotel altitude and orbital position. It would approach the hotel from below, as Figure 10 shows. The pilot would not have the distraction of seeing Earth behind the hotel during the approach. Minimal propellant would be expended by the craft during this safari even though it carries the passengers nearly 400 km from the hotel (Figure 11).

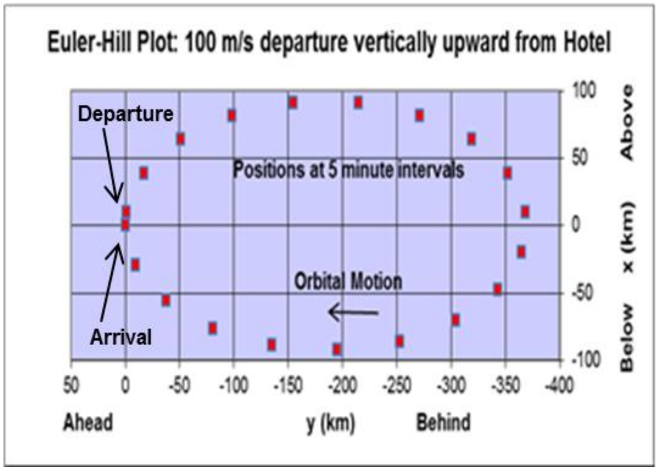

Figure 10. Euler-Hill Plot of Safari craft relative motion

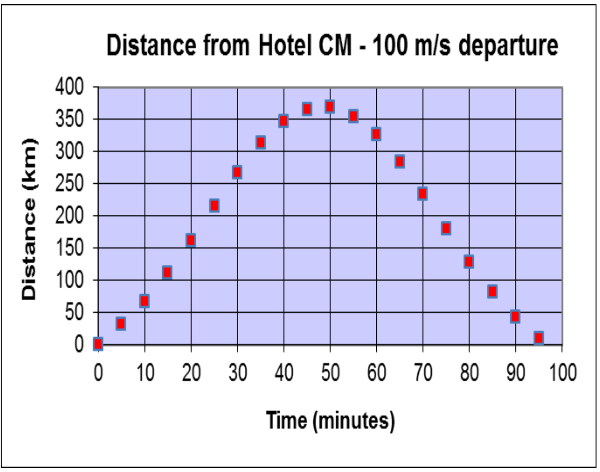

Figure 11. Distance to the Hotel during a Safari

The arrival of the craft would be timed via small navigational maneuvers by its astronaut-qualified pilots to coincide with the passage of the habitat through its rotation. A crane would swing out from the habitat to hook the craft when its relative motion and displacement both reached low values as Figures 12 and 13 show. The crane would swing the craft into a docking cradle for support in the 1 g environment and the guests would disembark.

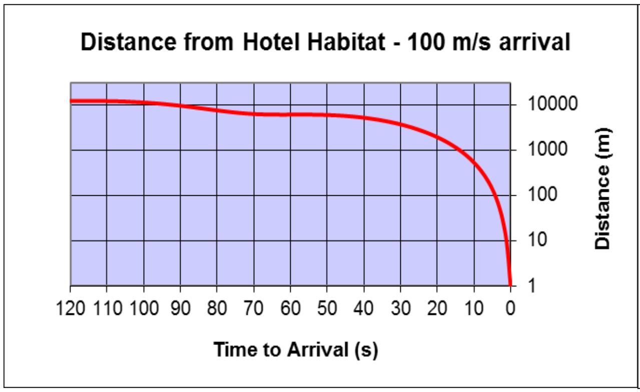

Figure 12. Distance during approach on return

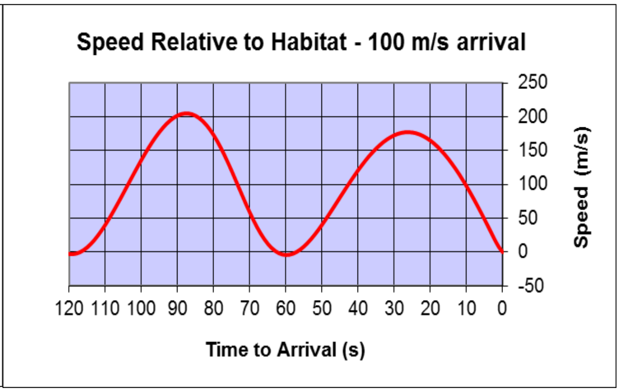

Figure 13. Speed during approach on return

If 97 minutes does not suffice for microgravity activities, integer multiples of this duration can be provided by traversing the loop in Figure 10 more than once. Safaris of various discrete durations would therefore be available. Activities would include floating, flying and otherwise playing in weightlessness, zero-g sports, playing with various toys and observing Earth. Viewing Earth from the confines of the hotel is not recommended due to the disorienting 1 rpm rotation rate. However it could be easily accommodated from the safari craft.

If the hotel operates at 600 km altitude with a linear spin speed of about 100 m/s, safari craft altitude would vary between 500 km and 700 km, as indicated by the ± 100 km altitude variation displayed in Figure 10. Figure 14 displays the range of latitude on Earth's surface that can be viewed as a function of altitude and Figure 15 displays a sample view from 600 km which covers Central America, part of South America and the Galápagos.

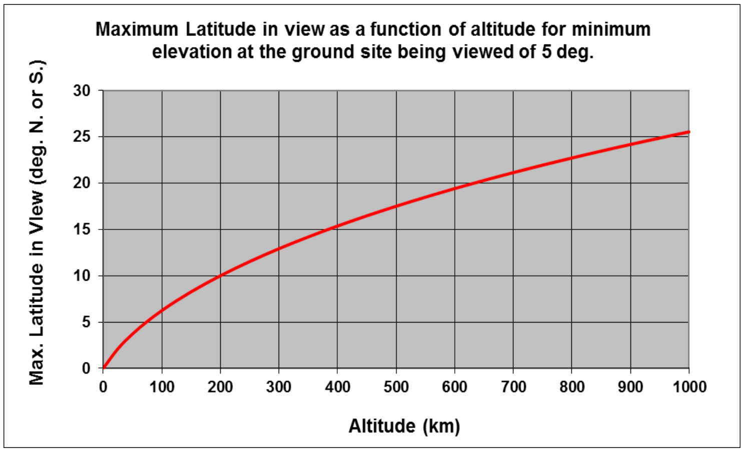

Figure 14. Visibility as a function of altitude

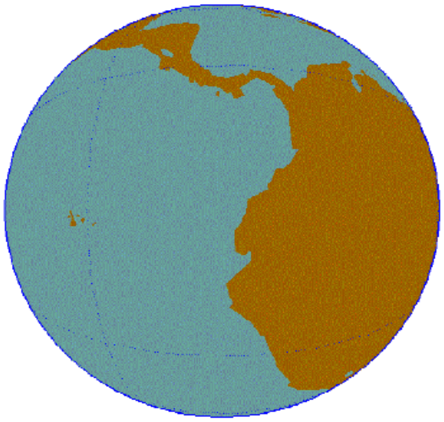

Figure 15. Sample view from 600 km

A concern is that many guests would want to view their own home town[23] or nation from space but this could not be accommodated from a space hotel in an equatorial orbit, except of course for guests from the nations near the equator. Analysis of the motivation of people to travel in space is beyond the scope of this paper, but if an equatorial-orbit hotel were at a suitable price point and a competing facility in inclined orbit could only be visited at a significantly higher price, possibly without the comfort of artificial gravity, then a considerable number of customers would opt for the equatorial space hotel.

Fascinating tropical storms could be viewed throughout their entire extent from this orbit and of course dramatic sunrises and sunsets could be watched multiple times each day.

When the craft lies within Earth's shadow there would be spectacular stargazing opportunities. There is an eclipse every revolution in a LEO equatorial orbit so one would occur during each safari. For a 600-km orbit each would last about 35 minutes or 36% of each rev throughout the year.

Both morning and afternoon microgravity safaris could be undertaken by adventurous guests, with a light lunch and a visit to the restroom back at the hotel in between. As with a hotel in a popular terrestrial vacation spot like San Diego, the surf would be at the beach, not in one's room or at the restaurant,

Following the afternoon's activities a guest could settle in for the evening and enjoy a fine dinner prepared by a gourmet chef and digested during a relaxing evening and a restful night. Some guests might prefer a busy morning filled with microgravity activities followed by a grand midday meal and then a siesta before indulging in a late afternoon or evening safari.

Guests from around the world would visit the space hotel and could remain on their own home time. All meals would be available at many times of day. The cleaning of rooms could go on around the clock if the guests were on a wide variety of local times and were out for activities at various times around a 24-hour clock. The staff might work on three 8-hour shifts as opposed to the day shift/night shift schedule in a terrestrial hotel.

C. HOTEL HABITAT LAYOUT

The probable physical background to the discomfort from head movement under artificial gravity introduced in part II, section D will now be discussed, for it has implications for the physical layout of the hotel.

This may be due to precession effects. When one shakes one's head "no" vigorously, an instantaneous spin rate with a magnitude of 50 rpm can be generated, first in one direction and then in the other. The nominal hotel spin rate is on a horizontal axis from the perspective of an upright subject, so it is a cross-axis with respect to the vertical axis about which one shakes one's head as Figure 16 indicates.

If the hotel's spin axis were parallel to an axis emerging from the subject's chest as shown in Figure 16, then the total angular momentum of the subject's head would be represented by a composite vector which is nearly but not quite vertical, either tipping the subject's head forward or backward depending upon whether the subject's head was rotating to the left or the right. This composite vector would always be nearly vertical but would deviate about 1° forward when the subject's head was rotating to the left and 1° backward when the subject's head were rotating to the left as Figure 16 shows.

To conclude, if one shakes one's head to indicate "no" in a rotating environment, one can end up also nodding one's head "yes". This unusual head motion effect has no analog in the normal terrestrial human experience. It is therefore the subject of concern for health and well-being.

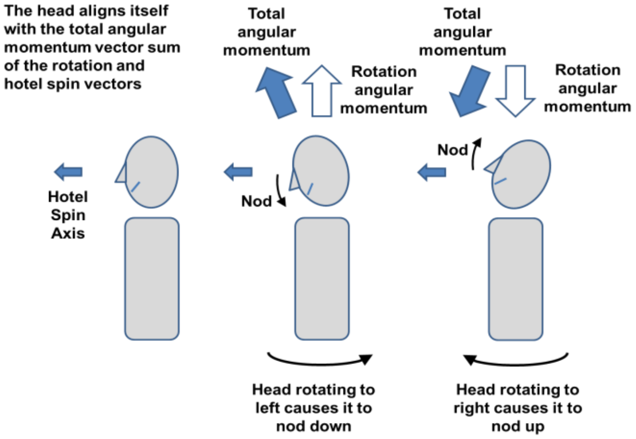

Figure 16. Precession from shaking one's head.

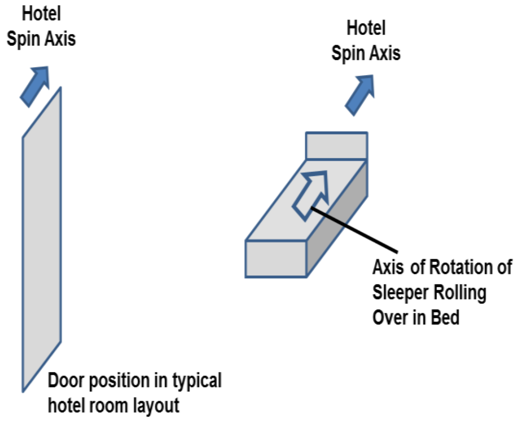

Figure 17. Bed layout to prevent precession

If a sleeping person turns over rapidly in bed, these effects might cause an unpleasant cross-axis motion unless the sleeper is lying parallel to the hotel spin axis as Figure 17 shows. This would eliminate precession since the sleeper's body rotation would be aligned with the hotel rotation. A person who is experiencing difficulty adapting to the effect displayed in Figure 16 could obtain relief by lying down for a while. It is therefore recommended that the length of each bed be aligned with the hotel spin axis.

The arrangement of the beds has architectural implications for the habitat. A bed in a hotel is usually arranged to have its length perpendicular to the direction one is walking when entering the room. If this traditional layout is followed, the doors to the rooms in the hotel would be aligned at right angles to the spin axis (Figure 17).

D. HOTEL COUNTERWEIGHT

The counterweight to the hotel habitat is assumed to be of equal mass and would therefore also be at an equal radius of gyration and therefore at 1 g artificial gravity. It would house equipment accessed electronically from the habitat using cables running the length of the connecting structure, as well as supplies and waste. These would be transferred to and from the habitat using off-duty safari craft. Instead of timing the arrival back at the hotel after a 97-minute flight to coincide with the position of the habitat, arrival would be timed to coincide with the position of the counterweight by making small adjustments to the orbit using the craft's thrusters. The need for an elevator or other regular conveyance along the length of the hotel tether or truss structure is therefore avoided.

Large deliveries of hotel supplies by cargo-only launch vehicles could be made to the counterweight instead of the habitat to avoid unnecessary disturbances. Waste would be dumped into low-perigee orbits for disposal into Earth's atmosphere using centrifuges aboard the counterweight, which would augment its approximately 100 m/s linear spin speed.

When the counterweight is in the back spin portion of the rotation cycle, disposal would be accommodated. Two counter-rotating centrifuges with linear spin speeds on the order of 50 m/s would accelerate matched loads of waste in opposite spin polarities to avoid disturbing the rotation of the entire hotel structure. The centrifuges would be synchronized so that both loads would have their velocity vectors opposite the direction of the hotel's forward orbital motion at the same time. At this instant both loads would be released simultaneously and would burn up in Earth's atmosphere within an hour.

Since the orbit is equatorial the debris footprint for the waste would be minimized. By scheduling the jettison events, waste re-entry would be confined to small area in the equatorial Pacific. Opportunities for waste disposal would be available every 104 minutes if the space hotel altitude were 600 km.

Departure from the hotel by safari or a craft returning guests to Earth could be achieved by placing the craft atop a large trapdoor which is opened very quickly by mechanical means and permits the craft to "fall" away from the structure. Arrival from Earth is more complex: this would involve establishing an elliptical orbit which intersects that of the habitat at a point in its rotation where the habitat is in the back spin portion of its rotation.

The arrival would occur at the apogee of the transfer orbit, which would have a velocity deficit of about 100 m/s with respect to the circular hotel orbit to match its linear spin speed. The rotation of the hotel is arranged to have the back spin segment on the earthward side (Figure 1). Variation of position and velocity with respect to the habitat during arrival would be similar to the profiles displayed in Figures 12 and 13 for returning safari craft.

E. CONTINGENCY OPERATIONS

In an emergency the habitat would be disconnected from the rotating hotel structure and, as previously discussed in part II, section E, enter an elliptical orbit. The habitat would retain its approximately 1 rpm rotation rate, which could hinder docking of rescue craft in contingency situations, but is not expected to hinder departure of escape craft. Here we observe yet another advantage of a low spin rate for the hotel: to facilitate emergency operations. The habitat would have the capability to de-spin itself and assume a stable attitude, but it need not be operated to evacuate all guests and non-essential personnel.

The highly-skilled, astronaut-trained core team would remain aboard the habitat to maintain damage control and assess conditions as long as any hope remained for repair. This crew would then restore it to operation. It is probable that the counterweight would include the maneuvering capability to rendezvous with the habitat and would therefore be crewed as well. The first priority would be to locate the trouble and effect repairs necessary to preserve the safety of the core team and the integrity of the hotel. Then the structure would be re-assembled under microgravity conditions and its integrity verified before it is accelerated to its operational spin rate. After 1 g artificial gravity is restored and the structure has been inspected, the hotel staff would return and clean up.

The core team and the pilots for the safari and transfer craft might include astronauts taking extended leave from the U.S. and other space programs. This would enable them to gain experience and additional hours in space between missions. The general manager of the hotel would probably be a highly experienced former astronaut. At dinner this individual might host a Captain's Table as on a cruise ship.

F. COMMUNICATIONS

Communications with the hotel could be maintained at all times by relaying signals, including high definition TV, through geosynchronous (GEO) spacecraft. These could be commercial communications spacecraft constructed by SSL and its competitors for owner-operators interested in providing this lucrative service. Many existing owner-operators already possess GEO constellations providing coverage all around the equator.

The beam footprint to serve the space hotel could be quite narrow and cover only a modest area on the surface of Earth since the hotel ground track would be confined to the equator, thus providing a high flux density fixed beam for economical operation. Steerable spot beam antennas could be used as well.

The vehicles used to transfer guests from Earth to the hotel and for safaris would also remain continuously in touch via GEO spacecraft. During ascent and return to Earth the guests could play videogames, send and receive tweets, e-mails and other communications, or view entertainment. This would help them avoiding dwelling on the novel microgravity environment, which might help avoid Space Adaptation Syndrome.

G. GOVERNMENT CUSTOMERS

Some hotel guests might be astronauts-in-training. These professional individuals could also be housed in the counterweight facilities. Extended microgravity safaris could be made available for astronaut-training, these could include rendezvous and docking with targets that are co-orbital with the hotel. Extra-vehicular activities (EVA) could be provided if spacesuits were brought along. Non-astronaut medical and other staff in the space program could work with the astronauts in the “shirt sleeve” hotel and safari craft as a part of the training effort.

IV. DEVELOPMENT OF THE SPACE HOTEL

Oberth’s vision in the early 1920s and the Gemini-Agena tethered experiment in late 1966 point the way to a rotating space hotel constructed in the form of a sling or rotating dumbbell as opposed to a wheel, with a habitat at one end and a counterweight at the other. A simple structure of this type, involving no movement of persons or materials within its architecture except within the habitat, has been assumed throughout this paper.

This concept could be developed over the next few years by launching a capsule on a conventional launch vehicle, such as the SpaceX Dragon on a Falcon 9 (F9) or Falcon Heavy, and the expended upper stage of the vehicle would serve as the counterweight.

Proper orientation of the capsule would permit the apparent down direction established by the centrifugal pseudo-force to be the same as that when the capsule is mounted atop the launch vehicle (LV), thus adhering to a common load path.

A number of upper stages, possibly from a variety of LV, could be assembled to augment counterweight mass for subsequent experimentation involving a dedicated habitat with room for standing, walking and performing calisthenics. The availability of a sizeable mass on-orbit would permit tests to be performed involving tethers and/or trusses with total lengths of 1800 m to generate 1 g artificial gravity with a 1 rpm rotation rate.

These experiments would verify whether artificial gravity can be a convincing substitute for the natural gravity at the surface of Earth for humans. Extended stays in this new class of space station and medical examinations following return to Earth of crewmembers would be undertaken as a part of this program. Laboratory animals not permitted in a space hotel would be maintained in this experimental station to evaluate whether they can grow and reproduce normally. Bacterial cultures would be studied to assure that new and more virulent strains are not generated in an artificial gravity environment.

As the hotel enters the later stages of its development, low-cost shipment of supplies might be achieved through cargo-only flights as mentioned in part III, section C. The Russian Soyuz, SpaceX F9 and Orbital Sciences Antares have demonstrated capability for this work. To function economically these and any new LV would be expected to operate at a very low price, possibly developed along the lines discussed in a previous paper[24].

V. LONG-TERM FUTURE PROSPECTS

While spin rates well below 1 rpm for 1 g artificial gravity are not feasible in LEO due to post-break orbital considerations, these could prove advantageous in other environments.

A. MARS MISSIONS

If there were multiple hotels in Earth orbit prior to a crewed Mars mission, one could be purchased by the space program, or put under a long term lease, and its rotation rate reduced so that artificial gravity equal to Mars surface gravity (0.38 g) is generated within its habitat. Reduction of the spin rate by roughly a factor of nine would accomplish this.

The particular hotel re-purposed for Mars work might have been retired after years of use, following the inauguration of more advanced later-generation hotels for private guests. The habitat might be modified to contain Mars surface simulant materials so astronauts can train for operations on that planet in a realistic environment.

A spacecraft en route to Mars or returning from Mars to Earth could make use of a very long connecting structure between the habitat and the counterweight since there would be no Earth altitude restrictions for any post-break orbital trajectory. This could provide Earth gravity with no issues about discomfort from head movement or any observable Coriolis acceleration to assure maximum long-term habitability. The lack of a quick-return capability to Earth would make this a priority.

Mars mission astronauts could be divided into teams. Some personnel would descend to the surface while others remain in orbit to provide real-time remote control of rovers and other devices, which is not possible from Earth due to the round-trip radiofrequency or light propagation delays of up to 42 minutes. Astronauts residing in Mars orbit could live and work in a facility with 1 g artificial gravity employing a very long tether or truss since there is no radiation belt around that planet. Material extracted from Phobos and/or Deimos could be used to provide ballast for the counterweight, radiation shielding and might be processed for other uses including tether or truss fabrication.

In the very long run tourists might visit the Mars orbiting facility and relax in its 1 g artificial gravity environment in between safaris down to the surface or to visit Mars' moons. This might be like taking an adventurous cruise to Antarctica today.

B. O'NEILL COLONIES

If the colonies envisioned by Gerard K. O'Neill[25] in the Earth-moon L5 Lagrange Point are constructed along the lines discussed here, these could incorporate tethers or truss structures with multiple-kilometer lengths, thus enabling rotation rates far below 1 rpm while still providing 1 g artificial gravity. This would enable colonists to avoid discomfort from head movement. Increasing the scale of the tether or truss would facilitate increasing the horizontal extent of the habitat, possibly to the acreage of a small farm or even larger.

This habitat might be large enough to provide a convincing simulation of being outdoors if a high dome can be mounted above its floor. This dome and floor would need to be made quite thick and heavy to provide radiation protection in lunar or deep space. O'Neill envisioned the use of lunar materials to construct these colonies and a novel means to obtain them from the moon are discussed in this paper[26] by the author. As discussed in the following section, materials obtained from asteroids might also be incorporated.

C. ASTEROID MINING COLONIES

Colonies architected as discussed in the preceding paragraphs could be constructed to be co-orbital with asteroids suitable for mining operations. Materials extraction would be performed under real-time remote control by persons residing within the colony habitat, while a few highly skilled professionals would perform hands-on maintenance on mining equipment and return to the colony for rest and relaxation. Asteroid materials would be used during the construction of the colony just as O'Neill envisioned the use of lunar materials to manufacture his L5 colonies.

These colonies could be used to manufacture a new generation of lucrative geosynchronous (GEO) commercial spacecraft out of asteroid materials to avoid the costs of launching bulk mass from Earth. Highly sophisticated spacecraft payloads might still be manufactured on Earth, but radiation shielding and certain equipment and propellant would be fabricated from asteroid products. These craft could be far larger than today's GEO spacecraft and might even include the capability to beam power to Earth as well as television and other signals.

VI. MATHEMATICAL APPENDIX

A. RIGID BODY ROTATION CONSIDERATIONS

The equations for rigid body rotation were obtained from Melissinos and Lobkowicz[27]:

$V = \omega R$ for linear spin speed V, where ω is angular rate and R is the radius of gyration (1)

$A = V^2/R$, for artificial gravity A, where V and R are defined above (2)

Equation (2) is derived from equation (1) in this source. It was of special interest in part II, section F because a person aboard the hotel who is walking or running can alter the V term if motion is in the direction of spin or opposite to it. The square term for V shows that if one is walking at 1.5 m/s and spin rate is 100 m/s will result in a change of acceleration amounting to 0.023 g for a 1 g artificial gravity environment.

Manipulating (1) and (2) yields equations for acceleration as a function of angular rate, angular rate as a function of acceleration and radius of gyration and angular rate as functions of acceleration and linear spin speed:

$$A = \omega^2 R \tag{3}$$

$$\omega = \sqrt{(A/R)} \tag{4}$$

$$\omega = A/V \tag{5}$$

Equation (3) shows that as one proceeds to a higher radius of gyration from going from one floor of the hotel to a lower floor, the artificial gravity level increases linearly with the radius of gyration since the entire hotel has a constant spin rate. A 10 m descent through 2 or perhaps 3 floors would increase artificial gravity by 0.01 g for a radius of gyration of 1000 m, which would be hardly noticeable.

Equation (4) shows that decreasing angular rate for a constant level of acceleration is difficult to achieve due to its non-linearity. For example, one must quadruple the radius of gyration to reduce angular rate by half.

Equation (5) shows the inverse relationship of angular rate and linear spin speed for a constant level of artificial gravity. To obtain a more modest angular rate for a 1 g environment a higher linear spin speed is required.

Melissinos and Lobkowicz[28] also include equations for Coriolis acceleration and precession, although a simpler treatment was applied here. Coriolis acceleration was found using the difference in linear spin speed over the span of distance an object is dropped. Precession effects are found by examining the angular momentum vectors associated with a body affected by simultaneous rotations around two axes and the sum of these vectors.

To assess Coriolis acceleration, a drop of 1.8 m, a reasonable height for a person, was considered. For a radius of gyration of 1000 m the fractional difference in linear spin speed between the release point and the floor below is .0018. For a 100 m/s nominal linear spin speed the speed difference would be 0.18 m/s. In a 1 g environment the time for an object to fall 1.8 m is 0.606 seconds. So the lateral displacement due to the speed difference is 0.18 multiplied by 0.606 or 0.11 m (4.3 inches). To accelerate an object from rest so that it traverses 0.11 m in 0.606 seconds requires an acceleration of 0.6 m/s^2 which is about 0.06 g. This is the Coriolis acceleration, whose magnitude as a function of hotel radius of gyration is shown in Figure 3. At this level is expected to be noticeable but not to pose serious issues.

B. ORBIT DYNAMICS CONSIDERATIONS

The equations for orbital motion were obtained from Bate, Mueller and White[29]:

$$v = \sqrt{(\mu(2/r-1/a))} \tag{6}$$

where μ is the constant of planetary gravitation or 3.986×10^{14} for Earth in MKS units, r is orbital radius and a is semi-major axis of the orbit. A radius of 6378.137 km was assumed for Earth, the equatorial radius, for conversion of radius to altitude above Earth's surface. Equation (6) is known as the "vis-viva equation".

$$r_p + r_a = 2a \tag{7}$$

where r_p is the minimum radius or radius of perigee, r_a is the maximum radius or radius of apogee and a is as defined above.

$$\tau = 2\pi(\sqrt{(a^3/\mu)}) \tag{8}$$

where τ is the orbital period in seconds, and a and μ are as defined above. This period can be converted into an orbital angular rate ω_{orbit} using the equation $\omega_{orbit} = 2\pi/\tau$

The synodic period is found from comparing the orbital angular rate and that of the Earth, ω_E. Earth completes a 360° rotation with respect to inertial space in 86164.09054 seconds.

$$\tau_S = 2\pi/|\omega_E - \omega_{orbit}| \tag{9}$$

Manipulating equation (6) yields an equation for orbital semi-major axis as a function of speed:

$$a = 1/(2/r - v^2/\mu) \tag{10}$$

This shows that increasing orbital velocity by adding in or subtracting rigid body rotation linear spin speed V from equation (1) can alter semi-major axis. However, if the linear spin speed is orthogonal to the orbital velocity and considerably smaller, for example 100 m/s for linear spin speed and 7560 m/s for orbital velocity in the baseline case in this paper, then the change to semi-major axis will be very small, as occurs in the Microgravity Safari cases. If the two are parallel, a modification of semi-major axis of about 200 km occurs for the baseline case in this paper.

Manipulating equation (7) yields

$$r_p = 2a - r_a \tag{11}$$

so if a 100 m/s reduction in orbital velocity is generated releasing a mass from the hotel during the back spin portion of its rotation (see Figure 1), leading to a reduction of semi-major axis by about 200 km in the previous paragraph but no modification to apogee radius, then perigee radius will decrease by about 400 km. From a 600 km initial altitude this is about as much reduction in perigee altitude as can be tolerated (part II, section E).

Equations (8) and (9) are manipulated to compute the orbital periods and synodic periods for the space hotel and the phasing orbit used to reach the hotel, which are needed in the computation of duration of a microgravity safari, transit time from Earth to station and launch window duration.

C. RELATIVE ORBITAL MOTION

The Euler-Hill equations for relative motion were obtained from Kaplan[30]:

$$x(t) = (1/\omega_{orbit})(dx_0/dt)\sin(\omega_{orbit}t)-[(2/\omega_{orbit})(dy_0/dt) + 3x_0]\cos(\omega_{orbit}t) + [(2/\omega_{orbit})(dy_0/dt) + 4x_0] \tag{12}$$

$$y(t) = (2/\omega_{orbit})(dx_0/dt)\cos(\omega_{orbit}t)-[(4/\omega_{orbit})(dy_0/dt) + 6x_0]\sin(\omega_{orbit}t) + [y_0 - (2/\omega_{orbit})(dx_0/dt)] - [3(dy_0/dt) + 6\omega_{orbit}x_0]t \tag{13}$$

The origin of the (x,y) coordinate system is a reference satellite, which will be taken to be the center of mass of the space hotel. x is a vector originating at this satellite in the radial direction away from Earth and y is a vector in the direction of its orbital velocity vector. The x- and y-coordinates of the safari craft relative to the hotel in Figures 10 were obtained from implementing equations (12) and (13) and these equations were used to obtain the results presented in Figures 11-13.

It is through the use of equations (12) and (13) that the role of the timing of a break in the tether or truss connecting the nodes of the hotel (Figure 1) can be assessed. Should the nodes be aligned with the vertical or x-axis, the linear spin speed has maximum effect in the y-direction, or dy_0/dt is of maximum magnitude.

This provides a non-zero value for the secular term at the end of (13). Therefore we have a separation between the nodes which increases with time since the two nodes will have dy_0/dt terms of equal magnitude and opposite sign.

However, if the nodes are aligned with the horizontal or y-axis at the time of the break, then dy_0/dt will be very small and there will be no such continuing divergence. Also, the periodic terms in (12) and (13) depend more weakly upon dx_0/dt than dy_0/dt. Thus, it will be simpler to reconstruct the hotel at a later time if the break occurs when the hotel nodes are aligned with the y-axis.

In part II, section E the notion of deliberate separation of the hotel nodes was discussed as a response to an emergency such as an uncontrollable fire. This would create a microgravity environment in the hotel to shut down the convective motion of air around the fire with the goal of quickly extinguishing it. Delaying this action by up to one-quarter of the hotel spin period or about 15 seconds so the hotel nodes would be aligned horizontally at the time of the break would enable the hotel to be reassembled more economically when it was safe to do so.

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