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David A. Quinn and David C. Folta

NASA/Goddard Space Flight Center

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A TETHERED FORMATION FLYING CONCEPT FOR THE SPECS MISSION

David A. Quinn* and David C. Folta†

The Sub-millimeter Probe of the Evolution of Cosmic Structure (SPECS) is a bold new mission concept designed to address fundamental questions about the Universe, including how the first stars formed from primordial material, and the first galaxies from pre-galactic structures, how the galaxies evolve over time, and what the cosmic history of energy release, heavy element synthesis, and dust formation is. Half of the luminosity and 98% of the post Big-Bang photons exit in the sub-millimeter range. The spectrum of our own Milky Way Galaxy shows this, and many galaxies have even more pronounced long-wavelength emissions. There can be no doubt that revolutionary science will be enabled when we have tools to study the sub-millimeter sky with Hubble-Space-Telescope-class resolution and sensitivity. Ideally, a very large telescope with an effective aperture approaching one kilometer in diameter would be needed to obtain such high quality angular resolution at these long wavelengths. However, a single aperture one kilometer in diameter would not only be very difficult to build and maintain at the cryogenic temperatures required for good seeing, but could actually turn out to be serious overkill. Because cosmic sub-millimeter photons are plentiful and the new detectors will be sensitive, the observations needed to address the questions posed above can be made with an interferometer using well established aperture synthesis techniques. Possibly as few as three 3-4 meter diameter mirrors flying in precision formation could be used to collect the light. To mitigate the need for a great deal of propellant, tethers may be needed as well. A spin-stabilized, tethered formation is a possible configuration requiring a more advanced form of formation flying controller, where dynamics are coupled due to the existence of the tethers between nodes in the formation network. The paper presents one such concept, a proposed configuration for a mission concept which combines the best features of structure, tethers and formation flying to meet the ambitious requirements necessary to make a future SPECS mission a success.

* Aerospace Engineer, Guidance-Navigation and Control Center, Code 572, NASA Goddard Space Flight Center, Greenbelt, MD 20771.

† Aerospace Engineer, Guidance-Navigation and Control Center, Code 571, NASA Goddard Space Flight Center, Greenbelt, MD 20771.

INTRODUCTION

Our current picture of the Universe at large is at best, incomplete. The answers to many of the most basic questions in cosmology remain elusive. What is the history of element formation and energy release in the Universe? When could life have first formed in the history of the Universe? It has been said that we are literally stardust, so when we study the origins of the elements, we are in a very real sense studying our own origins.

Interstellar dust has two effects on the light that reaches us from the cosmos. First, thermal emission from dust grains bathed in starlight produces the bulk of the far infrared emission that scientists wish to image. Second, through absorption and scattering, the dust attenuates the ultraviolet and visible emissions from galaxies and star and planet forming regions. Conventional optical telescopes provide essential but incomplete information. Nearly half of the luminosity and 98% of the photons in the post-Big Bang Universe are in the far-infrared and submillimeter wavelength range. That is to say, nearly half of the photons in the Universe are not being scrutinized to same fidelity as that of shorter, less prevalent wavelengths. This is not an intentional bias towards shorter wavelengths, merely the result of the fact that ability to study long wavelengths at high resolution has never been considered feasible, until now.

To address these science challenges, a science team led by several COBE (Cosmic Observer of Background Emissions) science team members (Mather, Moseley, Leisawitz) have proposed a 1 Km submillimeter interferometer mission called the Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) [1]. The SPECS concept has been presented to several panels and has been identified as one of the SEU vision missions targeted for launch after 2014. Over this last year, a team of scientists and engineers have been looking at what architectures could accomplish a mission of this nature. With this in mind, a workshop was held in College Park, Maryland in February 1999 to begin looking at the, requirements, issues and problems associated with just such a mission.

PROBLEM DEFINITION

Driving Requirements

The top level scientific requirements of the SPECS mission were provided by the scientists who first envisioned the mission. They are as follows:

- Spectral range from 40-500μm, 15 arc-minute FOV with resolution comparable to that of the Hubble Space Telescope.
- Capable of observing as much of the sky as possible.
- Capable of completing a single observation inside 72 hours.
- Minimum goal of 5 year mission life.

Hubble-Space-Telescope-class resolution in the sub-millimeter range implies a resolution of about 0.05 arc-seconds for the desired wavelength range from 40μm to 500μm. Selecting a mean frequency acceptable to the scientific community of 250μm as the design point, the approximate separation between the collection elements of the interferometer may be computed:

$$resolution = \frac{\lambda}{s} \qquad [1]$$

yielding a maximum separation of about 1031.3 meters, in turn becoming the maximum baseline requirement for the interferometer.

Theoretically, two mirror/collectors at the desired separation should be sufficient to accomplish the science goal; however, experience in ground based interferometry demonstrates that the single baseline provided by two light collectors may be subject to the effects of atmospheric or phase distortion of the wave front. To avoid this problem, typically three collectors have been employed resulting in three baselines. This permits phase distortion effects to be mathematically minimized using well established phase closure algorithms. Although there is no atmosphere in space, it is not yet known whether similar effects should be expected for as yet unknown reasons. Preferring to be conservative, this design assumes that three baselines are desirable for reasons similar to those discussed above and provide for redundancy concerns.

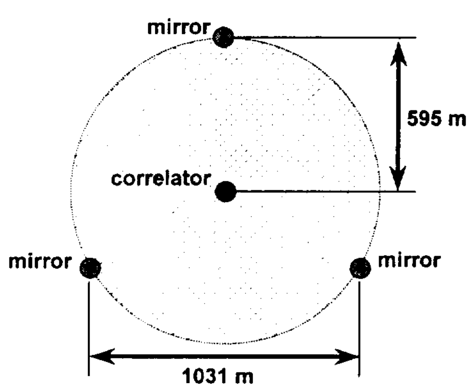

Figure 1. Three small mirrors form a single (595 meter radius) synthetic aperture.

The maximum separation between three mirrors has now been determined. Simple geometry tells us that the most efficient configuration of three such collectors is that of a regular triangle with a beam correlator at the center. Such a configuration yields an interferometer with a 1031.3 meter baseline or a synthetic aperture with a effective radius of 595.4 m (Figure 1). To be fully effective, the collecting mirrors must also be capable of movement within the plane perpendicular to the primary optical axis relative to the central beam correlator in such a way that permits collection of light over the entire area of the synthetic aperture.

Design Challenges

Operating four such vehicles to the control accuracy required in low Earth orbit (LEO) would be an expensive proposition to say the least. The amount of fuel needed to overcome relative orbital dynamics while maintaining the triangular co-planer formation of the separated vehicles, not to mention meeting the requirement to reorient the configuration so as to see as much of the observable sky as possible, would easily forfeit the five year mission life requirement. For similar reasons and others related to the clarity of astronomical 'seeing' in the near Earth environment and the cryogenic temperatures demanded of the science optics, it was decided that the optimal location for such a facility as SPECS would be the intermediate, co-linear Sun-Earth Lagrange Point, L_2. Still, operating a large formation such as this with the relative motions required over an extended period of time would be very fuel intensive, and now that fuel must be carried all the way to L_2. Further, the control requirements could potentially require constant correction thruster firings if some other means of maintaining the formation cannot be found.

Summing up, to meet the SPECS requirements, we need to design a facility which can be deployed at L_2, consisting of at least four spacecraft in a tightly controlled planer formation capable of maintaining an equilateral triangle whose sides can vary in length from virtually 0 to 1031 meters for each observation. An observation should take no more than 72 hours to complete. Finally, it should be capable of repeated observations of any part of the sky over a five year mission life.

A PROPOSED SOLUTION

Although there are literally an infinite number of possible configurations to choose from, we have selected one that satisfies the science requirements and is relatively easy to deploy and operate. We have settled upon a configuration that rotates the entire formation about the primary optical axis while each mirror is free to move along lines radiating out from the central beam collector Figure 2).

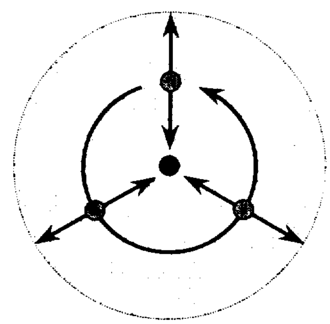

Figure 2. Relative degrees of freedom for the desired configuration.

In this way, conservation of angular momentum lends a hand in maintaining and controlling the spin rate of the central beam correlator, but only if the mirrors are somehow connected to the central beam correlator. Introduction of tethers into the design allows us to tie the formation together in a way that permits angular momentum to do most of the radial station keeping for us. Like a ball on the end of a string, centripetal forces will tend to keep the tethers taught and properly aligned with the central beam correlator. While conservation of angular momentum helps to solve one problem, it introduces another. As the radial length of the tethers change, the inertia tensor of the now connected formation changes and with it, the angular rate of the entire system. With only three outboard masses, the angular rate could be expected to increase by several orders of magnitude unless compensated. Compensation is accomplished by a triad of ballast masses equal to that of the mirrors themselves and positioned at the opposite ends of each tether. As the mirror is retracted, so the ballast mass is extended providing a momentum balance that will cause the angular rates to vary by only a factor of 2, which is manageable.

The proposed configuration, called SPECS-HEX employs three tethers, each of which is 600 meters long (Figure 3). At one end of each tether is a mirror and all the associated spacecraft hardware. At the other end is a ballast mass, a spacecraft in its own right whose primary function is to balance the mass of the mirror at the other end (Earlier designs employed six mirrors operated in two triads. This doubled overall productivity, but also doubled optics requirements on the central vehicle and was therefore deemed impractical). A kind of 'come-along' is employed on the central spacecraft allowing the tethers to be managed without the need to reel them in during every observation. Booms radiate out in six directions along the three axes of the tethers to provide momentum stiffness and a lever arm for performing reorientation maneuvers. It also serves as a framework to support a solar array and sunshield arrangement, as well as a stable platform for the mirrors to run along while performing observations at close quarters.

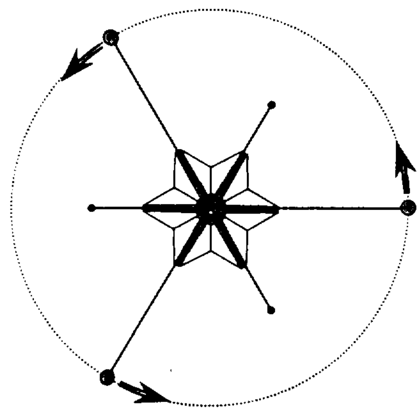

Figure 3. Balanced design of the SPECS-HEX configuration.

This design provides an excellent hybrid of the three major design possibilities. Structure at the center makes the system deployable and stable when the mirrors are closest together. Tethers allow distance to be well known and controllable while helping reduce fuel requirements on the overall system. Precision formation flying techniques may be applied as a means of providing navigation corrections to the positions of the mirrors and ballast masses relative to the central beam collector.

Operational Concept

This configuration of SPECS could be placed into low Earth orbit by the current Space Transportation System (Space Shuttle). Upon release from the shuttle, the spacecraft is spun up to about 90 rpm and a boost engine is fired putting it on a path that will carry it to L_2. Once there, the boost engine is discarded and some 100 days after the initial release from the Shuttle, a pair of 44 Newton ($I_{sp} \sim 300$sec) main engines fire for approximately 3 hours placing SPECS in a Lissajous trajectory about L_2 with a period of approximately six months. Periodic maintenance burns can impart approximately 3 m/s per year to keep SPECS on course over its expected 5 year lifetime.

Final deployment is accomplished in three stages (Figure 4). During each stage of the deployment, the mass of the system is distributed further from the center, slowing down the spin rate from its initial 90 rpm. In stage 1, the six booms fold open, sliding and locking them-selves into position, and the redistribution of mass causes the rotation rate to decrease. During stage 2, the booms are extended locking into their operational configuration, and the rotation rate of the decreases still further. Finally, during stage 3, the tethered spacecraft are released and the system rotation rate begins to approach the 0.01 rpm which is to be used during operation.

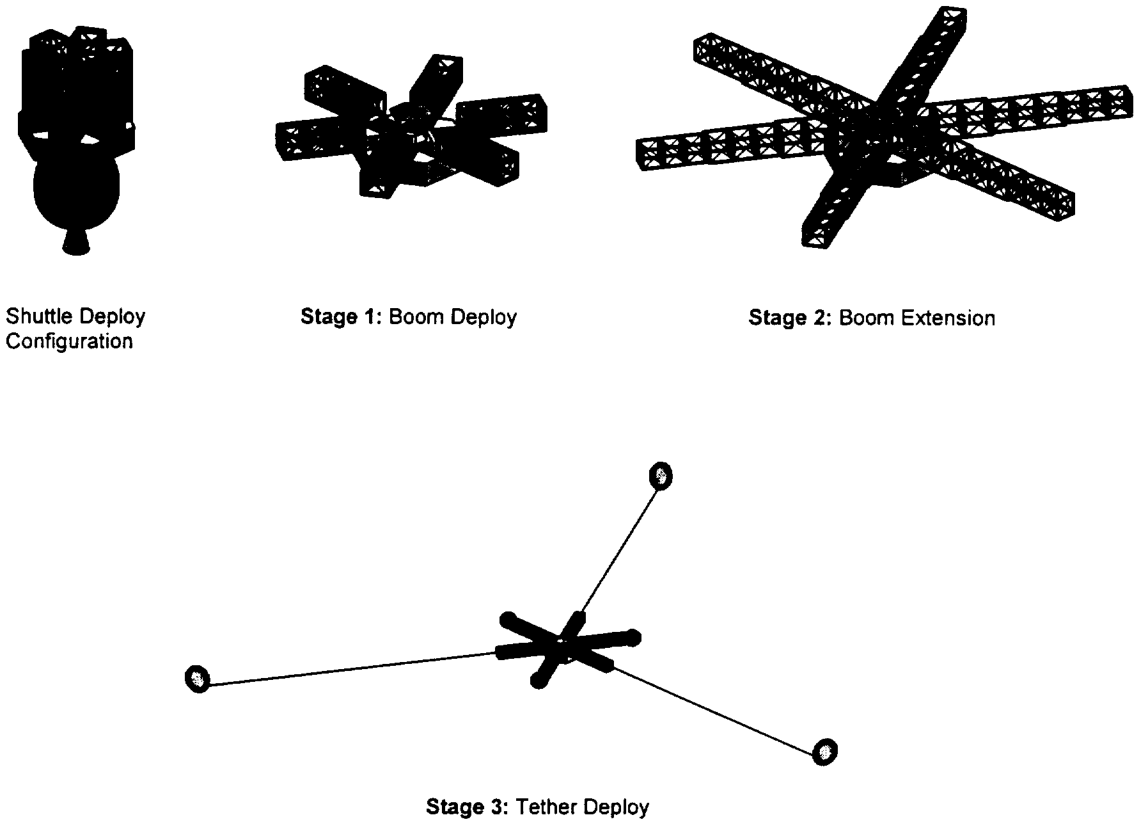

Figure 4. Launch configuration and deployment strategy of the SPECS-HEX concept.

Once on station at L_2, the fully deployed SPECS-HEX may begin its operational life. Outwardly, operations of the SPECS-HEX is a relatively simple matter. An observation is begun with the mirrors at their minimum separation from the central beam correlator and the ballast masses at their maximum distance. As the entire system rotates, the mirror tethers are extended at a rate which causes the mirrors to spiral out, completely filling in the synthetic aperture, as required. For this to work, the radial extension speed of the mirror tethers must be a function of the rotational speed which itself will change so as to maintain a constant angular momentum as the inertia tensor of the total system changes. When the mirrors have reached their maximum extension, the next observation may begin by reversing the process. By using three tethers each with a mirror and a ballast mass at each end it is believed that this gradual exchange of mass will contain rotation rates by keeping mass distribution of the entire system as balanced as possible. In this way consecutive observations of a single starfield can be made before re-orienting the system for the next observation.

Reorientation of the SPECS-HEX design may be accomplished in a relatively simple manner as well. This is executed by reeling in all six daughter spacecraft (all three mirrors and all three ballast spacecraft) to the ends of the structural deployment booms. While the spin rate will increase dramatically, science observations are suspended during this time so attention is focussed on the re-orientation. Once in the six daughter spacecraft are in place at the ends of the booms, the entire system may be treated as a single spin-stabilized spacecraft and reoriented accordingly. Consecutive thruster firings by the daughter spacecraft as the system rotates, will serve to retarget the overall system. Although each daughter spacecraft has a spooling mechanism at each end of the three tethers, we see here that operations of SPECS-HEX during observations does not require exercising the tether spools, this is only necessary for reorientation. During observations, the tethers need move only back and forth whereas during re-orientation they must reeled in. Since the platform will be reoriented only between observations, this saves wear and tear on the tether spooling mechanisms.

A SIMPLE MODEL

Intuitively, the SPECS-HEX concept appears to present an elegant solution to the problem of large, space-based imaging interferometry but the question remains can it work in reality? While a full three dimensional non-linear dynamics model will require years to formulate (and is well outside the scope of this conceptual paper) and simple model can be constructed in short order. For starters, we assume zero attitude and position error of the spacecraft mirrors and ballasts relative to the central spacecraft so that the outboard spacecraft formation always maintains themselves along the spokes of a perfect planer hexagon. If we then assume the tethers to always be taught, we can treat the entire idealized system as effectively rigid. Obviously this is not the true situation, but this assumption allows us to calculate the total mass of the system as well as the first order rotational inertia in terms of the distances from the central to outboard spacecraft. Nonlinearities and deviations from this assumption (introduced by the tethers) will be dealt with in subsequent analyses. Under this initial idealizing assumption, both the mass and the inertia tensor of the system may estimated as follows:

$$M_{total} = m_{center} + 3\left(m_{mirror} + m_{ballast}\right) + 3\left(\frac{m_{tether}}{l_{tether}}\right)\left[l_{mirror} + l_{ballast}\right] \qquad [2]$$

$$I_{total} = I_{center} + 3\left[\left(I + ml^2\right)_{mirror} + \left(I + ml^2\right)_{ballast}\right] + \frac{3}{4}\left(\frac{m_{tether}}{l_{tether}}\right)\left[l^3_{mirror} + l^3_{ballast}\right] \qquad [3]$$

Although the distance from any one mirror or ballast changes as observations are made, the sum of the distance from one mirror to its opposing ballast remains constant. As expected, the total mass of the system remains constant, but the rotational inertia will change due to the redistribution of mass. Maintaining angular momentum of the system as constant therefore requires the angular rate to change as the mirrors are brought closer and further away from the central spacecraft. Now the purpose of the ballast masses become clear. If only three spacecraft-mirrors were employed and the system rotating at an acceptable rate, rotation rates would increase by several orders of magnitude as the mirrors were reeled in towards the center. The ballast masses allow for a mass exchange to occur such that as the mirror is brought in, a ballast mass is extended. This reduces the variations in mass distribution and allows rotation rates to increase only on the order of about 2:1.

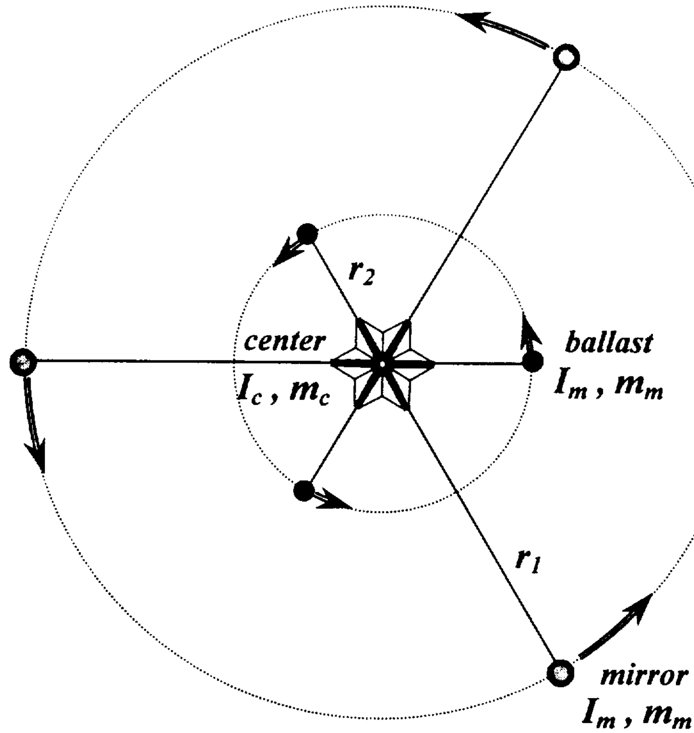

Figure 5. Assumed configuration for first order mathematical model.

As an example, let us assume the total mass of the system to be approximately 5000 kg, using 2000 kg as the mass of the central spacecraft leaving 3000 kg for the total of the six daughter spacecraft at 500 kg each. Allowing for a mass of 1.36 $\times 10^{-3}$ kg/meter for three 600 meter tethers adds only another 2-3 kg to the system and may be considered negligible, even though they will be carried in the mathematical development. The equations above now permit the inertia tensor of the entire system to be computed as a function of the distance of the daughter spacecraft from the central hub (assuming also that the center of the mother spacecraft is both the center of mass of the system and the origin of coordinates). Recognizing that completely filling the synthetic aperture requires that the each mirror follows a spiral path so as to minimize overlap as the system rotates, demands that radial position and angular position of the mirrors be related. To determine how the relationship changes over time, we recognize that a simple relationship between radial and angular position exists which will permit a complete fill of the synthetic aperture:

$$\theta(r) = \left(\frac{d\theta}{dr}\right) r + r_0 \qquad [4]$$

Take the time derivative:

$$\left(\frac{d\theta}{dt}\right) = \cancelto{0}{\frac{d}{dt}\left(\frac{d\theta}{dr}\right)} + \left(\frac{d\theta}{dr}\right)\frac{dr}{dt} + \cancelto{0}{\frac{dr_0}{dt}}$$

By definition $\omega \equiv \left(\frac{d\theta}{dt}\right)$, therefore: $\omega = \left(\frac{d\theta}{dr}\right)\dot{r}$ ...and since: $\omega = \frac{h}{I(r)}$

We may now define $q \equiv \frac{1}{\left(\frac{d\theta}{dr}\right)} \Rightarrow qh\,dt = I(r)dr$

$$qh\int dt = \int I(r)dr$$

$$qh(t-t_0) = \int_{r_0}^{r} I(r)dr$$

Recalling that the distance between a mirror and its opposing ballast mass is constant:

$$r_1 + r_2 = l \quad \Rightarrow \quad r_2 = (l - r_1)$$

...where r_1 is the distance between a mirror and the center and r_2 is the distance between the ballast mass and the center (Figure 5). Compute terms for r_2 in terms of r_1:

$$r_2^{\,2} = \left(l^2 - 2lr_1 + r_1^{\,2}\right) \qquad [5]$$

$$r_2^{\,3} = \left(l^3 - 3l^2 r_1 + 3lr_1^{\,2} - r_1^{\,3}\right) \qquad [6]$$

Substitute Eqs. [5] & [6] into Eq. [3]:

$$I(r_1, r_2) = I_c + 6I_m + \frac{3}{4}\left(\frac{m_t}{l}\right)\left[r_1^{\,3} + r_2^{\,3}\right] + 3m_m\left[r_1^{\,2} + r_2^{\,2}\right] \qquad [7]$$

Leaving the inertia in term of r_1 only. Rearrange Eq. [7] dropping the subscript on r_1:

$$I(r) = \left[\tfrac{9}{4}m_t + 6m_m\right]r^2 - \left[\tfrac{9}{4}m_t l + 6m_m l\right]r + \left[\tfrac{3}{4}m_t l^2 + 3m_m l^2 + I_c + 6I_m\right] \qquad [8]$$

Integrate Eq. [8]:

$$qh(t-t_0) = \int_{r_0}^{r}\left\{\left[\tfrac{9}{4}m_t + 6m_f\right]r^2 - \left[\tfrac{9}{4}m_t l + 6m_f l\right]r + \left[\tfrac{3}{4}m_t l^2 + 3m_f l^2 + I_s + 6I_f\right]\right\}dr \qquad [9]$$

For convenience, define A_0, A_1, A_2 such that:

$$qh(t-t_0)=\int_{r_0}^{r}\left\{A_2r^2-A_1r+A_0\right\}dr \qquad [10]$$

$$qht = \tfrac{1}{3}A_2\left(r^3-r_0^3\right) - \tfrac{1}{2}A_1\left(r^2-r_0^2\right) + A_0\left(r-r_0\right) \qquad [11]$$

$$qht = \left(\tfrac{1}{3}A_2\right)r^3 - \left(\tfrac{1}{2}A_1\right)r^2 + \left(A_0\right)r + \left(-\tfrac{1}{3}A_2r_0^3 + \tfrac{1}{2}A_1r_0^2 - A_0r_0\right) \qquad [12]$$

using Eqs. [10], [11] and [12] in Eq. [9] yields time as a function of radial position:

$$t = \left[\frac{1}{3}\frac{A_2}{qh}\right]r^3 - \left[\frac{1}{2}\frac{A_1}{qh}\right]r^2 + \left[\frac{A_0}{qh}\right]r + \left(\frac{1}{qh}\right)\left[-\tfrac{1}{3}A_2r_0^3 + \tfrac{1}{2}A_1r_0^2 - A_0r_0\right] \qquad [13]$$

If we set the mirror diameters at 4 meters, we find that there are constants of integration which remain undefined. This final ambiguity is solved by noting the scientists' desire for the mirrors to move gradually during observations. While the position of the mirrors will not be held fixed, the linear tangential speed of the mirrors is desired to be capped at approximately 1 m/s. From Eq. [13] above, a sixth order curve fit is employed to find radial position as a function of time. For this specific example, the equations have been set up and the total momentum of the system held constant, but that constant is tuned so as to yield maximum tangential rate of no more than 1 m/s, as requested. Parametric equations of radial and angular position in time may now be set up such that:

$$r(t)= (C_6)t^6 + (C_5)t^5 + (C_4)t^4 + (C_3)t^3 + (C_2)t^2 + (C_1)t + (C_0) \qquad [14]$$

$$\theta(t)= \left(\frac{C_6}{q}\right)t^6 + \left(\frac{C_5}{q}\right)t^5 + \left(\frac{C_4}{q}\right)t^4 + \left(\frac{C_3}{q}\right)t^3 + \left(\frac{C_2}{q}\right)t^2 + \left(\frac{C_1}{q}\right)t + \left(\frac{C_0}{q}\right) \qquad [15]$$

From which angular and radial rates can be easily computed:

$$\dot{r}(t)= 6(C_6)t^5 + 5(C_5)t^4 + 4(C_4)t^3 + 3(C_3)t^4 + 2(C_2)t + (C_1) \qquad [16]$$

$$\dot{\theta}(t)= \left(\frac{6C_6}{q}\right)t^5 + \left(\frac{5C_5}{q}\right)t^4 + \left(\frac{4C_4}{q}\right)t^3 + \left(\frac{3C_3}{q}\right)t^2 + \left(\frac{2C_2}{q}\right)t^1 + \left(\frac{C_1}{q}\right) \qquad [17]$$

So, for a given (constant) angular momentum we find that these equations describe a spiraling motion of the mirrors over time which will completely fill the synthetic aperture. It is interesting to notice that neither the radial or angular rates are constant. One might desire to set the radial rates at some constant value such that the tethers could reeled in and out at a constant rate. While this approach could be taken, it results in a very inefficient fill of the synthetic aperture taking far too long with a great deal of overlap if the rate is too low or leaving gaps in the fill if the rate is too high.

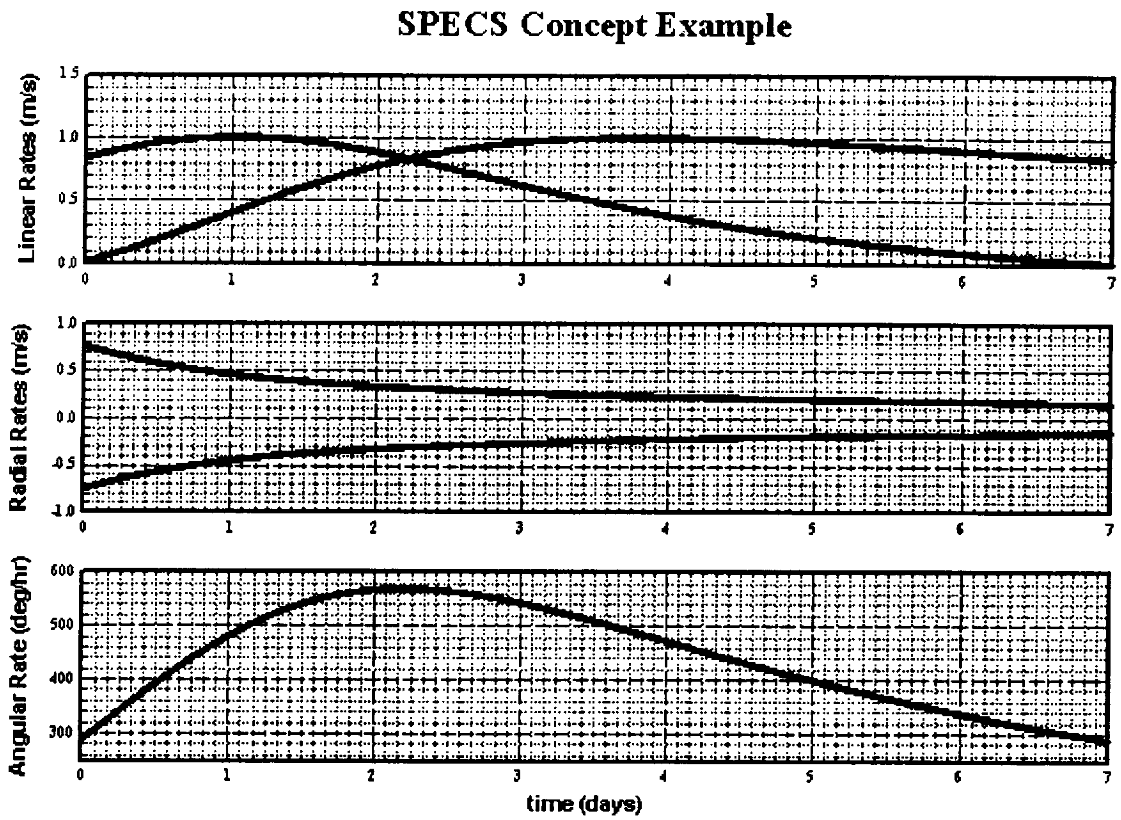

Figure 6. Linear, Radial & Angular Rate of the given mathematical model.

Figure 6 shows the results of these computations. The first graph shows the tangential rates of the mirrors and ballasts as an observation progresses. The total system momentum was tuned so that these curves (one for each end of a given tether) reach a maximum of 1 m/s, consistent with the desires of the scientists. The second graph shows the radial rates of each end of a given tether, or the speed with which the tethers must be pulled through the come-along at the central spacecraft. The last graph shows the angular rate of the system as a whole. Notice that the variation of angular rates ranges from about 300 – 600 deg/hr resulting in an efficient fill of the entire synthetic aperture in about 7 days.

If we wish to reorient the SPECS-HEX system, then all six daughter spacecraft must be reeled to a position at the ends of the central booms where they are held fixed to the central body. If the booms are assumed to be approximately 50 meters in length, doing this increases the angular rate of the system to about 1 rpm. Since observations can be assumed to be suspended during this operation, the 1 m/s tangential speed limit is no longer an issue. Once all the daughter spacecraft are secure at the ends of the booms, the system may now be treated as single spin stabilized spacecraft, for the purposes of retargeting. Each of the daughter spacecraft possesses a full compliment of thrusters, so a retargeting burn may executed by firing thrusters on any of the daughter spacecraft. If we wish to be capable of reorienting the system from any target to any other target in one day, we assume the maximum reorientation rate λ_{max} accordingly. We can then estimate the force required to initiate the reorientation to be:

$$F = \frac{\lambda_{max} I_{\perp}}{\Delta t \ r} \qquad [18]$$

where $I_{\perp}$ is the off-axis inertia, Δt the thrust duration and r the length of the boom. For this example a thrust of approximately 0.058 Newtons is required to initiate the reorientation and similar thrust is required to stop once the new target has been attained making a total 0.116 Newtons required per reorientation. After the new target orientation has been attained, the daughter spacecraft may be redeployed on their tethers and observations of the new target may begin. If we allow for one such reorientation (on average) every 10 days, we find that 20 grams of fuel per daughter spacecraft is more than enough to complete a five year mission. This remarkably low fuel requirement is due primarily to the long lever arm provided by the booms and the slow rate (λ_{max}) at which the reorientation is to occur.

It must be noted again that this very simple model was developed to parameterize the problem to first order. The tethers here are assumed to be rigid, effectively massless and always perfectly aligned along the axes of a planer hexagon. Under these highly idealized assumptions a mathematical model was developed in order to determine if it is even possible for the scientific requirements of such an observatory could be met.

IMPLICATIONS OF THE FIRST ORDER MODEL

Several implications come out of our first order model. First is that the science desire to complete an observation in 72 hours is subject to the efficiency of the observation. As we have seen, the 1 m/s tangential rate limit flows from the fact that a complete spiral scan of the synthetic aperture requires a minimum of seven days under the best of circumstances. If the 72 hour limit becomes a driving factor then either the 1 m/s tangential limit or the fully populated scan of the synthetic aperture must be compromised.

Secondly, since the radial speeds of the mirrors are not constant we can be sure that some method of reeling in and out the tethers at variable predetermined rates will be required. An efficient means of pulling in the outer spacecraft while releasing the inner ones at the same rate would need to be developed. Perhaps a 'variable come along' mechanism could be devised which would not require the tethers to be reeled in during observations.

Further, the fuel requirements seen in this simple model are reasonable. L_2 insertion and subsequent maintenance can be met with a minimum of 400 kg of fuel on the central spacecraft. Reorientation burns require only 20 grams per spacecraft for each of the six daughter spacecraft. While the true dynamics of the full tethered system have yet to be determined and the demands on any thruster based control system have yet to be established, there is nothing else preventing the SPECS-HEX configuration from meeting the mission objectives.

Finally, and perhaps most important of all, some means of controlling the outboard spacecraft relative to the desired formation is in order. For first order purposes, we have made simplifying assumptions about the tether being rigid and straight, neither of which is true in reality. The true non-linear nature of tether dynamics in a rotating system such as this will need to be more fully explored before any kind of control scheme can be designed and implemented. Obviously modeling the dynamics and control of such a complex rotating tethered system will be require a considerable amount of time and expertise to study, but this simple shows that the investment is worth the effort.

FUTURE STUDIES

Obviously, much more work must be done to fully explore the possibilities of SPEC-HEX configuration. Primarily, the non-linear dynamics of tethers under circumstances such as these must be more completely understood and a means of controlling the daughter spacecraft developed. Work at the Naval Research Laboratory in modeling tether dynamics [2] as well as efforts at the Goddard Space Flight Center in decentralized control methods [3, 4 & 5] are being examined in the belief that they may be adaptable to address the specifics of this problem. Tether deployment mechanisms will need to advance to permit deployment, retraction and re-deployment of tethers in the manner required of SPECS-HEX. Tether materials will need to endure the rigors of long term exposure to deep space and deployable booms will be required to complete the SPECS-HEX design. These are formidable obstacles, but with the proper expertise brought to bear on this most challenging problem, there can be little doubt that the concept of a large rotating tethered observatory can be brought to life.

CONCLUSIONS

The key conclusion of this cursory study is to confirm the possibility that a rotating tethered distributed spacecraft system is at least feasible and worthy of further investigation. Once tether dynamics are understood, and a means of control has been developed, we will be able to reap the substantial benefits offered in the ability to create enormous observatories with relatively small spacecraft. In this way, an economically viable means of examining the long wavelength emissions of the Universe to high precision will finally become available. As new and more detailed information becomes available, unexpected results will lead us to startling conclusions. Our understanding of Nature will increase as we paint a clearer picture of the Universe and our place within it.

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