MOST
(_M_icrovariability & _O_scillations of _ST_ars)

Canada's First Space Telescope

Part One

The Institute for Space and Terrestrial Science (ISTS), Dynacon Enterprises Limited and the University of Toronto propose that the MOST microsatellite mission be developed under the Canadian Space Agency's Small Payloads Program. MOST (which stands for Microvariability and Oscillations of STars) is a small space telescope. MOST will accomplish an important astronomical objective, gathering high-quality long-period stellar photometry data (measuring fluctuations in stellar brightness) for selected stars, from which stellar age, core composition, stability and presence of planets can be inferred. Because photometry places much less-stringent requirements on the telescope used than does imaging astronomy, this mission can be accomplished within the minimal mass, volume, power, data rate and cost resources available in a microsatellite mission.

This part of the proposal describes in detail the scientific objectives of the MOST mission and their significance, the context of these within the Canadian space science program, the nature of the instrument required to gather the necessary data, and the plan to gather and analyze these data.

Note: Dynacon has provided a considerable amount of confidential material relating to their business plans to develop attitude control system products and microsat buses for part 2 of this proposal. Also, Surrey Satellite Technology Limited has provided detailed pricing information relating to their UoSAT microsat bus product. This information should be treated as confidential, and should not be released other than to reviewers of this proposal.
The MOST science team does **not** object to the CSA circulating the MOST proposal title, abstract and science team membership.

1.1 Abstract

We propose a micro-satellite astrophysics mission to monitor rapid stellar variability, ranging from acoustic pulsations in Sun-like and magnetic stars to turbulent eddies in the winds of hot massive stars. Our concept of a simple robust 10-cm telescope with twin CCD detectors, placed in a Sun-synchronous orbit, would provide an unprecedented combination of high photometric precision (0.1 - 0.001%) and short time sampling (≤ 1 min) for stars as faint as $V \approx 8$, with a long uninterrupted time baseline (up to ≈ 2 months for a given star field in the orbital Continuous Visibility Zone). This offers the tantalizing prospect of making the first detection of rapid brightness oscillations in bright solar-type stars—a goal of solar and stellar astronomers for over twenty years—and using the techniques of asteroseismology to measure their masses and ages.

No ground-based telescope network (which must cope with the severe scintillation noise of the Earth's atmosphere and limited total time coverage due to weather and observatory scheduling) could match the performance of this micro-satellite. With the tragic loss of the EVRIS photometer aboard the MARS-96 spacecraft, there is no other funded space mission on the drawing board capable of this exciting science.

We envisage an initial mission of one year, during which about six star fields will be monitored. If the satellite life is longer and ground support is available, a wider variety of science goals could be satisfied, or the instrument could even become the heart of a high-profile CSA public outreach programme opened to guest observing proposals by high school students, amateur astronomy groups and others.

1.2 The MOST Team

To address the challenge of developing a high quality space science microsatellite mission on a frugal budget, a team comprising some of Canada's foremost space science and technology organizations has been assembled to carry out the MOST mission:

- The MOST science team is led by Principal Investigator (PI) Slavek Rucinski, a well-known Canadian observational astronomer (affiiliated academically with the Astronomy Departments of both the University of Toronto and York University). He has assembled a core science team of four astronomers, from across Canada as well as

the United States, to plan the MOST mission and subsequently analyze its data:

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- The Investigator Organization (IO) for the purpose of developing the MOST instrument is the Instrument Services Laboratory (ISL) of the Institute for Space and Terrestrial Science (ISTS) in Toronto, with whom Dr. Rucinski is also affiliated (the science team members will use their university department facilities to support each of their data analysis activities). The ISL (contact: John Connor, Program Manager, 416-665-5431), which is experienced in project management and optical instrument design and testing, and has been involved with past CSA Space Science instruments, will design the MOST instrument under Dr. Rucinski's supervision.

- The MOPITT laboratory at the University of Toronto, supervised by Physics Department Professor James Drummond (contact: 416–978–4723), will manufacture and carry out some testing of the MOST instrument, using their clean-room and thermal vacuum test chamber facility.

- The MOST team's industrial team member is Dynacon Enterprises Limited (contact: Dr. Kieran Carroll, Manager, Space Projects, 416–667–0505), a Toronto space technology company experienced in developing space systems for example, the DICE Space Shuttle experimental microsat platform that Dynacon is developing for the CSA's Space Technology branch. Dynacon will lead the design of the overall MOST mission and development of the MOST bus. Dynacon is well-known as a Canadian leader in the field of spacecraft attitude dynamics and control, who is currently working with Surrey Satellite Technology Limited in England to develop advanced microsat attitude control capabilities (discussed further in Section 2.1.2); it is this experience which will enable MOST to achieve the pointing accuracy needed to achieve its objectives.

- The University of Toronto Institute for Aerospace Studies (UTIAS) will team with Dynacon to develop the bus for MOST, carrying on the successful Dynacon/UTIAS collaboration under which the DICE microsat is being developed (contact: Prof. Peter Hughes, Space Systems Engineering, 416–667–7719). UTIAS has for many years been Canada's foremost school for space engineering; they are currently investing in a significant expansion of their Space Systems Engineering program, which will allow significant new facilities and graduate engineering student resources to be brought to the MOST bus development effort.

- The help of the Royal Astronomical Society of Canada (RASC) has been enlisted to organize and run the Public Outreach component of the MOST mission.

- The Canadian Space Agency will, of course, be a key member of the MOST development team. The MOST development plan foresees direct involvement by personnel from the Space Science Branch, as well as the Space Technology and Space Operations branches, in developing and testing the MOST equipment, preparing the MOST satellite for launch, and operating it once in orbit.

A noteworthy feature of the development team's structure is that it is small (the bus development team will include at most 10 to 15 personnel, and the instrument team 5 to 10) and geographically compact (all of the development team members except for the CSA are located within Toronto, and the lead organizations ISTS, Dynacon and UTIAS are within 3 km of each other). This is a crucial element in the plan to minimize the MOST development costs and schedule. Proximity of team members to each other, and minimization of team size, enables a flattened management structure and frequent, informal meetings between all team members; these are two key approaches to breaking the "business as usual" satellite development paradigm, that are cited by the microsat development organizations in other countries that have been most successful in achieving drastic reductions in costs.

1.3 Basic Objectives

The basic objective of the mission is achievement of a long, uniform series of uninterrupted observations of a few well-selected, bright stellar objects. The micro-satellite will monitor stars for months without interruption by the poor weather and the day-night cycle imposed on a single Earth-bound observatory, and will be the first satellite specially constructed to explore the niche of small-scale variability of stars. There are no existing and planned experiments of similar nature. The only similar instrument which could address the same scientific niche was lost in the MARS-96 disaster. The MOST mission is an outstanding opportunity for space astronomy as very few astronomy missions can usefully be done using a low-cost, micro-spacecraft.

1.4 Relation to Astronomy Research in Canada and Worldwide

Photometry is one of the three main streams of observational astrophysics, the other being imaging and spectroscopy of stellar objects, and addresses the matter of precise brightness measurements. The subfield of time-sequence photometry is relatively less explored, as it requires large amounts of observational time and

excellent weather. Yet, this is the only area where great scientific contributions can be made with the use of small instruments. This is the niche that we want to explore with MOST. The results would have universal worldwide ramifications, but must be considered in the context of astronomy reasearch in Canada.

The number of Canadian astronomers is more than 300. Virtually all use data and profit from space missions as the rapid development of this discipline to a large extent is due to space astronomy experiments. Canadian astronomers have participated in almost all international experiments from the beginning of space astronomy, by contributing to scientific programs and by using and analysing the data. However, Canada has not had its own astronomy mission. Currently, all astronomy experiments supported by the Canadian Space Agency through its Space Science Program, Ottawa (FUSE, ODIN, Space VLBI) belong to the category of International Missions. Such missions have been initiated by scientists in another country who invited Canadian scientists to participate. The Canadian scientists and the Canadian industry contributes to these missions by providing small but key components, at the level of typically 5% to 15% of the total costs and efforts related to the mission.

In the "Space Astronomy Plan" prepared for the CSA by the Joint Subcommittee on Space Astronomy in 1990, the mode of operation through participation in the International Missions was considered the most cost effective. At that time JSSA was chaired by Professor Gregory Fahlman of UBC and thus the plan is frequently called the "Fahlman Plan" (it is available from the Canadian Astronomical Society WWW page: http://www.astro. umontreal. ca/~casca/ via "Officers and Committees," CASCA Committees "Space" or directly from: http://www.astro. utoronto.ca/~rucinski /jssa.html).

However, JSSA made a very important recommendation (page 3, second paragraph) of direct application to this proposal:

"Participation as a junior partner in missions largely developed elsewhere will establish a Canadian presence in space astronomy and develop an experienced base of scientific and

technical personnel. Our long term goal is, within 5 to 10 years, to reach the point where we can initiate a mission and carry the majority of the project development within our scientific and industrial community. For such a goal to be practical, the CSA should have in place a mechanism, including access to necessary funds, whereby a large science project can be appropriately received, evaluated and, if justified, financially supported."

The applicants believe that the current Small Payloads Program is an ideal tool for a modest implementation of these words written 6 years ago.

1.5 Scientific Justification

The age of the Universe. The search for planets around other stars. The deaths of massive stars in supernova explosions which can produce black holes. These are topics which generate excitement among both the astronomical community and the general public. They are also topics which depend directly or indirectly on our understanding of the evolution and dynamical behaviour of stars, from the use of pulsating Cepheids to measure distances of far flung galaxies to recognising the surface activity on cool stars which can mask or mimic the signature of planetary companions.

1.6 Stellar Oscillations

Stellar variability is a matter of perspective. For example, in one sense, our Sun has been remarkably constant in its energy output over a very long period of time, providing a stable environment for the development of life on Earth. Yet, the Sun is also a variable star which exhibits subtle wave motions at its surface. These pulsations offer a unique insight into the Sun's hidden interior—thanks to fledgling techniques similar to those used by seismologists to probe the Earth's structure. Helioseismologists have the advantage that the gaseous structure of a star like the Sun is inherently much simpler than the complex, heavily stratified interior of the Earth with its solid and liquid components. However, they have the distinct disadvantage of having to observe the solar oscillations from afar. Such observations require long

uninterrupted time coverage which has only recently been achieved through networks like GONG (the Global Oscillations Network Group). These rely on telescopes distributed in longitude around the globe to avoid the day-night cycle imposed on solar data from a single observatory. So far, helioseismic data have pinpointed the depth of the solar convection zone, charted the Sun's internal rotation, and helped show that the origin of the Solar Neutrino Paradox appears to lie in the particle physics and not in errors in the Standard Solar Model.

Astronomers would like to apply such techniques to other stars. Even without the spatial resolution possible for the disk of the Sun, the integrated surface vibrations of stars can yield valuable information about their internal structure and age. The new techniques of asteroseismology represent a powerful tool for stellar astrophysics. However, to detect and interpret Sun-like vibrations in other stars will demand photometric precision of at least a few parts in 100,000, time resolution of a minute or less, and nearly continuous monitoring over months.

Stellar oscillations have been described in several monographs. The most recent summary of the observational state is contained in the review by GAUTSCHY & SAITO (1996). The review stresses what can be learned about normal stars by studying their pulsations; it also reveals how many types of pulsating stars are currently not explained in terms of mechanisms driving their pulsations.

1.7 The Diagnostic Power of Asteroseismology

The best estimates of the ages of stars come from fitting isochrones (theoretical models of the luminosity and temperature distribution of stars of a wide range of masses but uniform age) to observed colour-magnitude diagrams of star clusters. When applied to the globular clusters in the halo of our Galaxy—representing the earliest generations of star formation we can sample—this technique sets a lower limit to the age of the Universe of about 15 billion years. However, some recent estimates of the cosmic expansion rate, the

Hubble Constant H_0, imply that the Universe would not be older than about 12 billion years. Which is right? Asteroseismology gives us an independent way to measure the age of a star which is still burning hydrogen on the main sequence, and hence to test stellar isochrones.

If the star is oscillating in modes of low degree $\ell < 4$ (fewer than 4 nodes on the surface), but high radial overtone $n \gg \ell$ (many nodes interior to the star), then its frequencies will be almost equally spaced from one another. According to TASSOUL's (1980, 1990) asymptotic theory, the fundamental spacing $\Delta \nu_0$ depends on the sound wave travel time across the star's diameter, which is a function of the mean density of the star. If the effective temperature is known (through spectroscopy or multicolour photometry), then the radius and luminosity can be determined to high accuracy from this spacing. On the other hand, slight deviations from equal spacing, known as the small separation δ_{02}, are sensitive to the sound speed gradient in the stellar core. There, the gas is nearly isothermal (especially for a star with a convective core) and the sound speed gradient depends not on the temperature but on the composition. Since the core composition changes with main sequence age (as more H is destroyed to create He), this parameter is a "clock" which starts ticking when core H-burning begins.

If we can detect oscillations and resolve the fine structure in the eigenfrequency spectra of stars exhibiting high-overtone acoustic modes, we will have an independent check on the predictions of stellar evolution theory, especially if some of those stars are part of an open cluster. There would be two principal types of targets for this aspect of the mission: (1) bright solar-type stars (for which such oscillations are expected, based on the Sun, but have not yet been unambiguously detected) and (2) rapidly oscillating Ap (roAp) stars (strongly magnetic stars about 2000 K hotter than the Sun in which high-overtone pulsations have already been found).

Recent extensive reviews on the progress and potential of the rapidly-expanding field of asteroseismology include BROWN & GILLILAND (1994), KURTZ (1990) and MATTHEWS (1991, 1993a,b, 1997).

1.8 Stellar Variability on Longer Time-Scales

All of the target stars (both Sun-like and strongly magnetic) are expected to have surface spots of varying size and flux contrast, akin to sunspots. As the stars rotate, these spots are carried across the disk facing us and we should see periodic modulation of the starlight. Normally, ground-based photometry is sensitive to only the largest spots. The precise measurements during this mission will be able to detect much smaller, lower contrast features in the photosphere. Since the rotation periods of Ap stars and young solar-type stars are typically measured in weeks, we should be able to sample several cycles. The photometry can be compared with coordinated ground-based spectroscopy of the same objects to construct an "image" of the stellar surface.

1.9 Luminous Stars: Constraints from Continuous Photometry

Luminous stars tend to be among the most massive stars, as a consequence of the strong luminosity-mass dependence: $L \propto M^3$. For example, a star that is $10 - 100 \times$ more massive than the Sun will radiate $10^3 - 10^6 \times$ more energy per second than the Sun. Therefore, massive, luminous stars exhaust their nuclear fuel and evolve much more quickly than their low-mass cousins. Extremely high luminosities along with high photospheric temperatures generate very strong stellar winds among the most luminous stars. Instabilities and large-scale structures appear to be the norm in such stars and their winds. At the origin of these, the best candidates are stellar radial or non-radial pulsations and localized magnetic fields, rotating with the star.

The most exotic luminous, hot stars are the Wolf-Rayet stars. Their winds are at least $10 \times$ stronger than their massive O-type progenitors, with ratios of wind to photon momentum ranging up to a factor 50, compared to less than unity for the most luminous O-stars. It is currently believed by some researchers that radiation pressure alone is not sufficient to drive such strong winds, even allowing for multiple scattering. Stellar pulsations and rotating magnetic loops are the best

candidates for additional—possibly crucial—wind drivers. Even if radiation pressure should suffice however, one still needs an explanation for the radiative instabilities and large-scale structures seen in most W-R stars. Determination of pulsation and magnetic characteristics of W-R stars would have an important impact on our understanding of massive stars.

Pulsation periods in W-R stars are expected (MAEDER 1985, 1991) to lie in the range $\simeq$ 10 minutes (radial) to an hour (non-radial). Rotation periods should be of the order of a day or more. Nothing is known about magnetic fields. The existence of short period oscillations in W-R stars from ground-based work has been very controversial (see MOFFAT 1994). For example, one group (BLECHA ET AL. 1992) has claimed a low-amplitude ($\simeq$ 0.005 mag) periodicity of 10.5 minutes in the WN8 star WR 40, while other groups (ANTOKHIN ET AL. 1994, SCHNEIDER ET AL. 1994) have not been able to confirm this. Is this an indication that the phenomenon is sporadic or are there instrumental problems? On the other hand, two independent groups (ANTOKHIN ET AL. 1994; Rauw et al. 1996) have found possible evidence for a 3.5-hour period buried in the intrinsically noisy signal ($\simeq$ 0.1 mag) from the WN8 star WR 66. The main problem in these studies is that the data bases are sparse and and in addition may be affected by a combination of instrumental and atmospheric effects, that are difficult to disentangle.

With MOST, we could secure truly continuous coverage for the first time of some key bright single W-R stars, on time scales from minutes to weeks. Such coverage is absolutely essential, not only for a deep search for periodicities, but also to probe how they change with time. In the target list are included known strong variable single W-R stars with possible periodicities, likely related to rotation and pulsation, as well as known micro-variable single stars with known clumpy winds in which supersonic turbulence is believed to prevail. Of particular interest is the possibility of being able to quantify the nature of the variability in the stars with clumpy winds. Our previous attempts to do this in limited series of spectra using wavelet analysis (LEPINE ET AL. 1996) has met with some success. However, a much more robust data sample as could be obtained with MOST, will allow us to apply the same technique in a statistically much more viable fashion, with potentially far-reaching results on

the basic nature of supersonic wind flows from hot stars.

Another very promising way to probe structures of W-R winds is via non-photospheric eclipses in W-R +O binary systems with periods in the range 2-20 days. In such systems, the bright O companion shines through varying parts of the W-R wind as it orbits, without actually eclipsing or being eclipsed by the W-R star's photosphere. This gives a more localized view of variability of the W-R wind. Previous work (LAMONTAGNE ET AL. 1996) shows that this technique is quite feasible, not only to reveal local structures, but also for viable determinations of the orbital inclination (important to get the stellar mass, when combined with the Doppler radial velocity orbit) and the mass-loss rate of the W-R star, independent of clumping effects (in contrast with most other methods). Good candidates are included in the target list.

1.10 Microvariability Inside and Near the Instability Strip

Ever since the study of Alpha Cyg by LUCY (1976, ApJ, 206, 499), it has been evident that what are often considered constant, non-variable stars may exhibit a low-amplitude pulsation of complex character, at least when compared to Cepheids and RR Lyr variables. Lucy analyzed an old set of 144 spectra of Alpha Cyg taken in 1931 to find a complex set of up to 16 modes in the low-amplitude variations of its radial velocity. Similarly, BUTLER (1993) found that Gamma Cyg, another presumed non-variable star, varies with a period of about 11 days and an amplitude of about 200 m/s. Thus Gamma Cyg resembled a classical Cepheid, except for the very low amplitude -- by two orders of magnitude!

However, variables like Alpha Cyg and Gamma Cyg have been classified as classical cepheids and Polaris is a good example with an amplitude of only 800 m/s, and similarly low-amplitude light variation. So although microvariability of stars in that part of the HR diagram is well documented, there remains the nagging question of its nature and origin. The underlying reason for this has not been so much lack of interest, as lack of long, uninterrupted runs of high precision photometry or

spectroscopy: all available data either lack the coverage, or the necessary precision. Therefore it has not been possible to study the modal behaviour (if any) or temporal variation of the variability in these stars.

Evidently the spectroscopic observations of the needed precision, while possible, will require unjustifiably large resources of large-telescope time (on several sites). Hence photometry is the better choice, being equally informative.

The questions to ask with this study will be: (1) whether the variability is that of Cepheids or RR Lyr (with their modal behaviour); or (2) whether it is indeed different from (1) and pertains more to the atmospheric properties of luminous stars in that temperature range. If the answer is positive on (1), that will have very important implications for the understanding Cepheid pulsation and hence their qualities as primary distance indicators in the Universe. Alternatively, a positive answer to (2) will help us understand the dynamics of the atmospheres of giants and supergiants (in this temperature range), and give us important constraints to their model atmospheres (e.g., sources of line broadening and effect on atmospheric opacities and mass loss).

1.11 Extra-Solar Planets

Recently, radial velocity variations of tens of m/s and periods of days have been detected in a number of bright solar-type stars. These have been widely interpreted as due to the presence of unseen Jupiter-mass planets in unusually close orbits around these stars, although high-overtone gravity-mode pulsations cannot be entirely ruled out at present. If the solar-type stars in our sample have similar planetary companions, photometry with a precision of 0.003% may reveal them through (1) shallow eclipses less than 1% deep, if the orbital plane lies near the line of sight, (2) changes in the total light of the system as the planet goes through a cycle of phases as seen from Earth, or (3) in certain cases, low-level backwarming of the star's photosphere by the planet. If the velocity variations are in fact due to low-amplitude pulsations with periods of days, the signature of this will also be evident in the photometric data.

A search for extra-solar planet would be the most ambitious application of MOST and could be contemplated only for the later stages of the mission, after the full in-orbit characterization and calibration of its instrument. Obviously, to achieve the high accuracy of observations, we would have to bin the data into much larger intervals than normally used. A photometric detection of a signal in stars with known planets (such as 51 Peg or τ Boo) would have a tremendous scientific importance and visibility. Thus, although MOST will be targeted initially onto variable stars described in the previous sections, we would attempt to keep the possibility of a search for extra-solar planets high in our list of possible targets.

1.12 Why Go to Space?

The main scientific drivers of this space satellite proposal are:

- The elimination of atmospheric scintillation, which is the dominant noise source preventing ground-based telescopes from reaching the desired photometric precision for many asteroseismic goals; and,
- The need for long, uniform series of continuous observations.

The photometric noise in the signal from a space-based instrument has characteristics which are extremely well behaved and predictable. Since the data will contain stellar variability signals at levels close to the measurement noise, this is a very important advantage which cannot be achieved by splicing data from different telescopes in a global network. The reliable detection of stellar oscillations at amplitudes of about a millimagnitude and timescales of a minute is generally limited not by photon noise, but terrestrial atmospheric scintillation. Since the atmospheric noise is definitely non-white and has an approximately ν^{-2} frequency-dependence, it is difficult to identify both low- and high-frequency stellar oscillations from rapid photometry at the millimag level. However, from orbit, the noise sources are typically white, and there is no scintillation component with which to contend.

A space-based platform makes it feasible to monitor stars for months without interruption by poor weather or the day-night cycle imposed on a single Earthbound observatory. Long strings of data allow one to extract very low amplitude periodic signals from the noise through techniques like Fourier analysis. The gains are really spectacular for coherent signals, but can be fully achieved for equally-sampled data. Also, to derive the maximum information from the eigenmode spectrum of a high-overtone pulsating star, we need high frequency resolution ($\Delta \nu \leq 0.5 \ \mu$Hz). This allows one to distinguish the fine splittings and frequency deviations caused by slow stellar rotation, magnetic fields, and the composition of the core (which is sensitive to the star's main sequence age). International collaborations involving many telescopes at different geographical longitudes, such as WET (the Whole Earth Telescope; see NATHER ET AL. 1990) can overcome the day-night cycle by combining data from many observatories located at longitudes around the world. But the practicalities of weather and coordinating observing time at so many telescopes have limited runs of an entire global network to about a week. South-pole observing stations have so far proven effective only for the Sun.

The need for long, uninterrupted observations was recognized recently by ESA in their support of the EVRIS photometer (with photoelectric detector) launched aboard the Russian MARS-96 probe (BAGLIN 1997). This photometer would have been able to obtain continuous rapid photometry of a few selected bright stars (with many science goals in common with this project) but only for the few months of the mission's interplanetary cruise phase. Tragically, this experiment was a casualty of the MARS-96 disaster.

1.13 Experiment Design

1.13.1 The Instrument

The MOST mission will consist of only one simple instrument (Figure 1.1), fully integrated with the satellite bus. This will be a small telescope of about 10 – 15 cm in diameter equipped with twin CCD detectors. (The exact size of the telescope will depend on results of the Phase A study; we assume here a baseline aperture of 10 cm.)

The telescope will feed two CCDs: one for data collection with integrations typically every 10 – 100 seconds, and one for attitude control with readout every 0.1 seconds. They will be identical and fully programmable and exchangeable. The light will be split either by a semi-transparent mirror or by a spectrally-dividing dichroic mirror. The choice will be made in Phase A as this decision requires a more extensive study: The semi-transparent mirror would assure full ex-changeability of detectors while the dichroic would permit better (spectral multiplexing) utilization of quanta. In the estimates below, for simplicity, we will assume that each CCD will receive half of the total signal. We assume that the CCD detectors will be 1 K x 1 K in size (see below), which makes them basically off-the-shelf items. The field of view will be 0.5 degree with 1.8 arcsec per pixel. For proper sampling, the images will be appodized to FWHM $\approx$ 2.5 – 3 pixels. The CCD's will be cooled, passively, to about -30°C to -50°C.
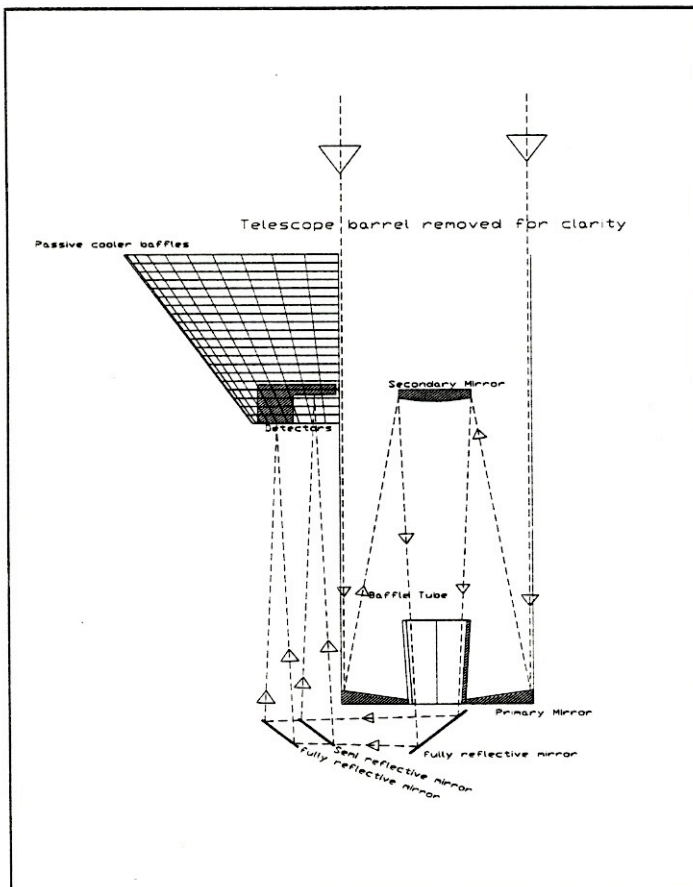

Figure 2.1: MOST Instrument

1.13.2 On-Board Operations

The spacecraft will point the telescope on the target to about 0.01 degree. Information about instantaneous pointing—sampled at the rate of 10 times per second by the "attitude CCD"—will permit integration of the signal within a box on the "data CCD" whose typical integration times will be 1 to 100 seconds. The measurements from the "data CCD" will be done continuously for periods extending between 2 weeks to 2 months, depending on the location of the object within the Continuous Visibility Zone (see the Section on the orbit below). Since the attitude control system can provide stability to 0.01 degree, the baselined window size on the "data CCD" is 0.05 degree = 180 arcsec (side dimension) or about 100 x 100 pixels. Possibly, the second (rim) window around the object window would have to be integrated as well to obtain information about the background and to evaluate the net stellar signal. However, information about background could be also obtained from single ground based observations, with MOST providing only information about variability (with arbitrary but determinable offset in brightness).

1.13.3 Expected Signals

The energy flux F of a star with visual magnitude m in the photometric band V (550 nm, bandpass 89 nm) is:

$$F = 2.5 \times 10^{-4} \times 10^{-0.4m} (D/10 \text{ cm})^2 \text{ erg/sec}$$

where D is the effective telescope diameter. Assuming conservative values for the optical efficiency of 0.5, the CCD quantum efficiency of 0.5, and fixing $D = 10$ cm, we obtain the total expected signal in electrons for 10 sec integrations per CCD:

$$S = 1 \times 10^8 \times 10^{-0.4m} \text{ electrons/10 sec}$$

The stellar magnitude scale is logarithmic; for each magnitude difference of 2.5, there is a drop in signal by a factor of 10. Thus, the expected signals for a 10 sec integration will be: $S = 1 \times 10^8$ electrons for $m = 0$ and $S = 6 \times 10^4$ for $m = 8$ (our limit for roAp stars). This signal must be sampled by about 10 pixels at any moment (the sampling of the PSF will be slightly above the Nyquist: FWHM $\approx$ 3 pixels in each direction) and should not saturate the detector, which can be

controlled by the integration time of the detector. The integration time will be set constant for a given object for duration of its observations, which will be typically two weeks to two months.

1.13.4 Performance Levels vs. Amplitude

The proposed observations will target the stellar *variability* so that requirements on the accuracy are less stringent than for most photometric observations of stars. For stellar photometric observations, the accuracy is typically about 0.5 to 1% and maybe as low as 10 to 20% for absolute measurements. Because the MOST measurements will form time-sequences with the interesting component contained in the variable (A/C) component of the signal, it should be possible to limit systematic errors to be comparable to or smaller than the random errors.

We consider here the following measurement errors: the finite "depth" of the CCD pixels, the readout noise, the photon noise and the detector non-uniformity. The typical well depths of the CCD detectors are about 2 x 10^5 electrons. Thus, for 10 second integrations, the saturation will take place at $m = 4.2$; for 1 second integrations, it can be shifted to brighter stars of $m = 1.7$. (Since two of our proposed objects have ≈ 0, we will have to consider even shorter integrations; we would prefer not to use neutral filters to avoid moving parts in the satellite). At these levels of the signal, the readout noise will be unimportant (less than about 50 electrons per pixel) with modest free-space cooling of the detector (to about -30°C to -50 C). The only source of random noise will be the photon shot noise which can be evaluated from the Poissonian statistics as $N \propto \sqrt{S}$. Thus, the signal-to-noise ratio will simply scale as $S/N \propto 1/\sqrt{S}$. Since we will always adjust the integration time to levels of about 10,000 to 100,000 electrons per pixel per readout, and with the PSF spread over about 10 pixels, the expected S/N per observation will be $S/N \approx 300 - 1000$. Higher S/N can be obtained by adding up successive n observations, with a gain in S/N scaling as $\propto \sqrt{n}$. Thus, for one minute observations, the expected $S/N \approx 770 - 2500$. Translated into errors, this will correspond to observational precision of $0.0013 - 0.0004$ mag per one minute observation.

Since the image will move over the CCD, on-board correction for CCD sensitivity non-uniformities must be performed. This is normally done by a procedure called "flat-fielding" which involves division by an image of uniform brightness distribution (this can be a smeared image of the clouds or of the full Moon). The first flat-field image on board of MOST would come from the ground, pre-flight calibration. This will be improved during the initial stages of the mission, as the quality of the flat field image is very important.

In contrast to sources of uncertainty described above, the flat-fielding can introduce non-random errors and thus lower accuracy of the measurement. The ground-based experience (GILLILAND ET AL. 1993) shows that flat fielding to $S/N \approx 300$ can be achieved. Since the MOST instrument will be very stable, we will able to achieve an even better S/N ratio. Besides, the PSF will extend over about 10 pixels, so that the influence on the final photometry can be improved by a further factor ≈ 3 times, leading to our intended goal of $S/N \approx 1000$. Thus, the expected relation between precision and accuracy of the MOST measurements should involve scaling by a factor of the order of $\sqrt{2}$.

The worse-case error estimates are therefore $\pm 0.001 - 0.003$ mag, deteriorated to $0.0014 - 0.005$ mag by the flat-fielding uncertainties. These can be considerably improved by binning, but with corresponding loss in the high-frequency detection capabilities.

1.13.5 Performance Levels vs. Frequency

Three numbers characterize the frequency content of the final data: the highest and the lowest frequencies and the spectral resolution.

The observations will be made with selectable (but constant for a given object) time resolution between 1 and 100 seconds. Thus, the Nyquist, high-frequency limit will be 0.005 to 0.5 Hz. All low frequencies up to this limit will be available. For one month of MOST observations, the formal low-frequency end will be at 0.4 μHz. This should in principle correspond to the spectral resolution, but because centroids of "spectral-lines" can be normally localized to higher accuracy than the formal frequency interval, the actual resolution may be higher. NATHER ET AL. (1990) quotes the spectral resolution of 0.5 μHz as achievable for 10 day spans. We would definitely lower this number for total durations of the order of one month to about 0.15 μHz. We note that the spectral resolution strongly depends on the duration of un-interrupted data and this aspect is more important than the frequency of data taking, allowing considerable freedom in a-posteriori binning of the data to improve the S/N of the mode definition.

1.13.6 Data Analysis

The photometry data will be analysed using Fourier analysis techniques developed for WET, as described by NATHER ET AL. (1990). The great advantage that we will have over WET will be in the equal time-step sampling of the data, permitting full utilization of the convenient properties of the Fast Fourier Transform (FFT), in place of Discrete Fourier Transform (DFT). DFT is computationally extremely demanding, yet its mathematical properties are not as well defined as for FFT. Also, because the data for one target will form just one string of numbers, there will be no phase shifts between the individual observatories, which in WET analysis, require special shifts in complex Fourier Transforms.

Long duration of MOST observations will offer particularly high accuracy for determination of amplitudes of coherent oscillations. The gain scales roughly with the square root of the number of individual observations. If a single 10-second observation would provide accuracy measured by $S/N \approx 300 - 1000$ (as discussed above), then the gain from observing a single-mode over one months will be of the order of 500, giving the final (per mode) S/N of 150,000 to 500,000. This translates into the mean errors of (2-10) parts per million. We note that the consortium of observers (similar to WET) studying M67 obtained a rather exceptional accuracy of about 7 parts per million utilizing 4-metre class telescopes (GILLILAND ET AL. 1993). A more typical number is 20 parts per million, even for such long campaigns as that of KURTZ ET AL. (1989) which collected 580 hours of observations.

1.13.7 Filter Selection

The V-filter has been selected here as the most popular one in astronomical photometry, permitting comparison with ground-based archival photometry, but this could be replaced by the I-band filter which better matches the peak sensitivity of the CCD. Also, the Phase A study will consider the wide filter used aboard the Hipparcos astrometric satellite, which would admit more photons and will become (as of 1997) a de-facto new photometric standard bandpass.

1.13.8 Science Data Telemetry

The attitude control system fed by the "attitude CCD" will permit the software system to follow the image on the "data CCD." The size of the software aperture for integration of the signal will be about 100 x 100 pixels (the exact size will be determined in Phase A). Thus, each observation, with integrations in the range typically between 1 and 100 seconds will provide one number. For one day of observing, there will be thus about 864 to 86400 separate numbers, an amount which will present absolutely no difficulty for one-per-day telemetry. In the case of cluster photometry, a handful of target stars would be isolated in the field by sub-rastering, so the telemetry load would increase by less than a factor of 10. This more complex operation mode will be considered during Phase A. At present we baseline observations of just one target at a given time.

In addition to simple photometry with basic extraction done on board, as described above, the satellite will have a provision of transmitting the whole image. We consider here a baseline detector of 1024 x 1024 pixels, so that the telemetry channel should be able to transmit occasionally files of the size of 2 Mbytes (assuming 2 bytes deep) within typically 5 – 10 minutes of the ground contact. This mode will be necessary for identification of stellar fields; this will be done only initially, in the first field acquisition, and then a few times per year, when changing targets. It may also be useful for checking the health of the detectors by sending the current flat-field images. (The flat-field images can be obtained by pointing the satellite at the Moon and then moving it to smear the irregularities of lunar topography).

The satellite will transmit the data as a short string of numbers once or twice per day, during dawn/dusk direct telemetry links. The amount of data per day will not exceed 10^5 numbers, which would present no problems for telemetry as slow as operating even the 9600 baud rate for direct contacts lasting a few minutes. This mode of operations will last for several weeks or months and would be the normal mode for prolonged observations of one object.

1.13.9 Field of View and Pixel Size

The attitude detector will require a large field of view, of the order of 0.5 degree (1800 arcsec). The diffraction resolution of a 10 cm telescope at optical wavelengths is about one arc-second. For precise photometry good sampling of the images is necessary. In order to reconcile these numbers and to preserve the small size of the CCD of 1K-pixels per side (i.e., pixel size 1.8 arcsec), we propose that the optical system provides appodization (controlled smearing) of images. This will insure an identical shape of the Point Spread Function (PSF) over the whole image. We note that simple de-focussing is not acceptable as it would produce images whose profiles would depend on distance from the optical axis of the telescope. The baseline size of their images would be characterized by the PSF with FWHM ≈ 2.5 – 3 pixels.

1.13.10 The Orbit

The satellite will be pointed at an object within the Continuous Visibility Zone (CVZ) of its orbit. The CVZ is basically the part of the sky in the pole of the satellite orbit which is visible from orbit without Earth eclipses. It is defined by a cone whose opening depends on the position of the local horizon from the orbit.

Every orbiting telescope has a CVZ; Since one object can be followed for prolonged periods of time, observations in the CVZ are considered about twice as cost-effective for the HST scheduling as non-CVZ observations (cf. the most current set of Hubble Space Telescope documents: Cycle 7 Proposal Documents, Part 1: Policies and Procedures, Para.6.4, and Part 2: The Hubble Space Telescope, Para. 14.1, both at http://www.stsci.edu/ under "Proposer" and "Cycle").

The angular size of the CVZ depends on the altitude of the satellite, h. The radius r of the CVZ is given by:

$$r = \arccos\ (R/(R+h))$$

where $R = 6378$ km is the radius of Earth. The CVZ moves in the sky following the precession of the satellite orbit. In the case of HST, the precession takes 56 days, resulting in durations of the CVZ observations limited to maximum of 6.5 days. The two CVZ's are located at declinations plus and minus 61.5 and have diameters of about 6 degrees for durations of continuous visibility longer than 3 days.

Sun-synchronous orbits are orbits where the ascending node of the longitude precesses, mainly due to the J_2 harmonic component of the Earth gravitational field, with the rate exactly equal to the difference between sidereal- and Sun-centred systems. Of particular importance is a subset of Sun-synchronous orbits which follow the instantaneous Earth terminator, i.e., the dusk/dawn line. For such orbits the CVZ is almost exactly away from the Sun, which leads to avoidance of thermal and optical degradation effects due to solar illumination: one side of the satellite would be fully illuminated by the Sun while the other could point at any object within a relatively large cone of the CVZ. The Sun-synchronous, terminator orbit would be optimal for the proposed experiment not only from the point of view of satellite thermal stability, ease of passive cooling of the detectors and avoidance of extensive baffle systems, but mainly because it would assure long duration of observations in a relatively large cone of the CVZ. The zone would very slowly scan the elliptical sky at the rate of one degree per day, the reflex motion of the solar motion on the sky. The Sun-synchronous orbits are realized by a selection of a mean-altitude/inclination pair. For example, the altitude $h = 400$ km, $I = 97.0$, gives the radius of the CVZ about $r = 20°$, while for $h = 1000$ km, $I = 99.5$, the radius is $r = 30°$. We would prefer not to go above 1000 km as the charged-particle density in the van Allen belt increases very rapidly above that altitude.

We propose to launch MOST as a secondary payload in one of relatively frequent launches of satellites utilizing Sun-synchronous orbits (such as RadarSat-2, $h = 785$ km, $r = 26°$). However, the concept of the mission is not limited to such orbits as any orbit providing large CVZ could be utilised by MOST. This circumstance is convenient, as it leaves considerable freedom in choosing the partners who would accept MOST as its secondary payload. The final choice of objects will be done after selection of the launch vehicle and orbit for the primary mission with which MOST would be launched.

1.13.11 Attitude Control

During normal operations, the attitude control system will insure stability to 0.01 degree i.e., 1/50 part of the field of view (0.5 degree). The photometric data will be collected within a software aperture of about 0.05 x 0.05 degree.

The initial, first orientation of the satellite will be done using the Sun as a reference point: The satellite will be equipped in Sun-sensors which will give the initial signal for orientation away from the Sun. Then, the normal acquisition process will follow with the slew to the first program star. Slewing of the satellite, envisaged as an operation done only a few times per year, will be through an open-loop control system utilizing reaction wheels. After re-orientation obtained by preset reaction-wheel loads, the attitude system will lock on any star in the field and current image of the sky will be sent down for a human identification. This could take up to a few days as the image dumps would be slower (the image files will be 2Mbyte in length, assuming the 2-byte depth). After identification, a corrective manoeuvre will be programmed to a new, final position of the satellite.

1.14 Relation to Other Similar Programs

1.14.1 Relation to Whole Earth Telescope (WET)

WET is the only instrument which currently attempts to pursue science which we envisage for MOST. However, the performance of WET is limited by several factors, which results in a different scientific niches for MOST and WET.

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- The extinction characteristics of non-white atmospheric scintillation will always remain in ground-base data. The slow variations in extinction are removed to some extent in WET through use of differential photometry, but some effects due to differing air masses between program and comparison star cannot be taken into account.

- WET is a consortium of moderate and large-size ground-based telescopes. It specializes in observations of crucially important, well-selected objects which are *not too bright*, as such targets would create problems with saturation of detectors. The stars must be also faint enough to reach sufficiently large density of objects for a proper comparison-star selection. This limitation to faint, but important stars (such as pulsating white dwarfs) is the best strategy for WET, but it leaves out bright stars—about which we know the most. MOST will not require any comparison stars.

- WET requires a large team of observers from many countries to collaborate by allocation of their telescopes to observations of a common object for durations of typically two weeks. This is not an easy organizational task, and still not everything can be organized and arranged a priori. Because of the weather and instrument failures, the current runs of WET last typically equivalent of 5 – 7 days (WINGET ET AL. 1991, 1994, KEPLER ET AL. 1995); only one run achieved 289 hours over 2 weeks with interruptions (PROVENCAL ET AL. 1995).

- In spite of participation of the observer teams consisting of dozens of observers, WET cannot achieve high efficiency, as blocked scheduling of many telescopes (which are normally used for other programs as well) must involve complex negotiations and agreements. The planned efficien -cy of WET is one or two targets per year (NATHER ET AL. 1990), which is confirmed by the actual numbers of publications with results from WET.

- WET will always experience problems of stitching together observations made with telescopes of different aperture. This affects the signal-to-noise ratio from different sites as well as the extinction effects.

In conclusion, the scientific niches for WET and MOST are different, with MOST having advantage in duration of runs, in number of observable objects and in uniformity of data. The niches are not overlapping as MOST will observe variability of bright, otherwise best-studied stars while WET will remain the prime instrument for variability studies of faint, but somewhat special targets, such as pulsating white dwarfs which would be too faint for MOST.

1.14.2 Relation to Hubble Space Telescope

The current proposal is a logical continuation of concepts developed for CVZ observations of variable stars with the Hubble Space Telescope. Successful programs of searching for variable stars in globular clusters 47 Tuc and NGC 6752, each lasting a few days were made by GILLILAND ET AL. (1995) and BAILYN ET AL. (1996). We note, however, MOST and HST have different overall goals: HST is a multi-purpose observatory which serves a large community so that its operation time is extremely precious, while MOST will be extremely low cost (about 0.25% Hubble's cost), dedicated photometric-variability observatory. The CVZ observations of Gilliland et al. and Bailyn et al. were allocated relatively much telescope time because of the multiplexing character of imagery permitting observations of literally thousands of stars in one stellar cluster. The CVZ's of HST are small (diameter 6 degrees for 3 days of continuous observations) so that few equally interesting objects as 47 Tuc and NGC 6752 happen to be located in them and few stellar-astrophysics targets remain there. Also, all HST instruments have stringent bright limits so none of the objects proposed for MOST would be ever available for precise HST photometry. And finally, the rapid precession of the HST orbit limits any CVZ observations to at most 6.5 days (within a very small CVZ of about 3 degrees in diameter). Thus, high resolution of closely spaced mode eigenfrequencies is impossible with the HST observations. Therefore, although conceptually similar, the CVZ observations of MOST and HST have different overall goals, with MOST having a distinct advantage for precise studies of prolonged variability phenomena.

1.15 The Science Team and Flow of Data

In contrast to experiments in other disciplines of space sciences, astronomy experiments tend to involve many scientists from various research institutions. The reason is usually cost-effectiveness and abundance of diversified objects. Since the MOST project is very highly focussed on stellar variability, the science team is small, yet it retains the typical characteristics of involvement of astronomers from various research centres. The proposing Scientific Team consists of 4 astronomers located at Toronto, Vancouver, Montreal and Harvard. The major link is front-line research in stellar variability. The team has been organized especially for the current application, in recognition of a unique opportunity that the proposed research may play for astronomy in Canada and world wide. The present team is small mostly for efficiency of its management during the proposal phase. There are several other Canadian astronomers in university centres such as Victoria, Calgary, Manitoba, Western Ontario, McMaster, Laval, St. Mary's who are vitally interested in the mission, and who could directly profit from the data and who could contribute to the Phase A definition.

The organizational structure of the team building the satellite is described in Part 2 of the proposal. Rucinski will be the PI of the whole project, throughout its development and utilization of the data. He will be in charge of the project through (and possibly beyond) its nominal data-taking phase of one year with the typical level of involvement exceeding 75% of his time.

The team analysing the data will be: Rucinski, Matthews, Moffat and Sasselov, plus any scientist who would join during Phase A. All four scientists have research grants permitting funding of graduate students and Post-Doctoral Fellows. The Canadian members are NSERC grantees and Moffat is eligible for additional Quebec research funding. This funding will be fully used for analysis of data from MOST and no additional resources would be sought from CSA or other agencies.

The Scientific Team will select the final targets and will analyse the data according to the primary interests of the members (Rucinski and Matthews: solar-type stars, Matthews: roAp stars, Moffat: hot luminous stars, Sasselov: micro-variables in the instability strip). The typical level of involvement of the three scientists in the project will be 15% to 50%. We note that participation of Dr. D. Sasselov, a graduate of the University of Toronto, currently on staff at the Harvard University, is crucial in providing a liaison with the strong U.S. astronomy community and with the possible contributions of NASA or the world- famous Harvard-Smithsonian Center of Astrophysics.

The team members and their students will retain exclusive ownership of the data for ½ year after the respective dataset has been received; afterward, the data will be made public through mechanisms such as the WWW. If the mission continues after the first year, then the Scientific Team will co-opt other Canadian scientists and will provide mechanisms for a wider access to the data by other scientists and qualified amateurs. We expect that a successful experiment operating over one year will attract a large community of further users.

Because of strong visibility of astronomy and the fact that this will be a *first* Canadian astronomy mission, the general public may become interested and willing to participate. There exist several amateur groups in the country, with the best known Royal Astronomical Society of Canada in the lead, who have expressed a willingness to organize a contest for the best observing proposal for an astronomy club or a high school. Data resulting from such observations could be made public in real time further increasing the visibility of this experiment and of the CSA in general.

1.16 Observational Targets

Definite selection of objects for observations cannot be done at this time because it will depend on the location of the CVZ, which in turn depends on the satellite orbit. Since the launch of MOST is envisaged as a secondary payload of a large satellite, the orbit will remain unknown until later stages of the project. In this situation, the team decided to prepare a larger target list than necessary at this stage, as depicted in Tables 1.1 through 1.4. Since each observation may last as long as about 2 months, six objects will be needed for one year. This may have to be modified by time overheads related to acquisition of objects and by possibly smaller size of CVZ for orbits not exactly Sun-synchronous on the earth terminator

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Table 1.1: Solar-Type Stars

Source	Sp	RA(2000)	dec(2000)	V	Remarks
α Cen	G2 V	14 39 30	-60 49 00	-0.01	Unknown pulsation properties
α CMi	F5 V	07 39 12	+05 14 00	+0.38	Unknown pulsation properties
η Boo	G0 IV	13 54 36	+18 25 00	+2.68	Controversial detection of ≃ 10-min period

Table 1.2: roAP Stars

Source	RA (2000)	dec(2000)	V	Period (min)	ΔV	Remarks
HD 24712	03 55 16	-12 05 54	6.00	6.2	0.010	At least 6 eigen-modes
HD 201601	21 10 21	+10 08 00	4.68	12.4	0.003	At least 4 frequencies
HD 176232	18 58 47	+13 54 00	5.89	11.6	0.002	Multi-periodic
HD 60435	07 31 00	-58 00 00	8.89	11.4	0.016	Richest p-mode spectrum

Table 1.3: Hot Luminous Stars

Source	RA (2000)	dec(2000)	V	Δ V	B - V	Remarks
WR6	06 54 13.0	-23 55 42	6.94	0.1	-0.07	WN5, P=3.77 d, inhomog wind
WR16	09 54 52.8	-57 43 39	8.43	0.1	+0.25	WN8, multi-periods?
WR40	11 06 17.3	-65 30 35	7.85	0.1	+0.11	WN8, multi-periods?
WR42	11 10 04.1	-60 58 45	8.25	0.01	+0.06	WC7+07V, P = 7.86 d
WR79	16 54 19.8	-41 49 13	6.95	0.03	+0.01	WC7+07V, P = 8.89 d
WR103	18 01 43.2	-32 42 54	9.01	0.1	+0.03	WC9, possible period(s)
WR111	18 08 28.4	-27 15 10	8.23	0.01	-0.02	WC5, clumpy wind
WR134	20 10 14.2	+36 10 35	8.23	0.05	+0.20	WN6, P = 2.27 d?, inhomog. Wind
WR135	20 11 53.4	+36 11 52	8.36	0.01	-0.03	WC8, clumpy wind
WR139	20 19 32.2	+38 43 54	8.10	0.3	+0.38	WN5+06, P = 4.21 d
WR153	22 18 45.7	+56 07 35	9.08	0.05	+0.27	WN6+O, P = 3 & 6 d (quadr.)

Table 1.4 Micro-Variables in the Instability Strip

Source	RA (2000)	dec(2000)	V	B - V	Remarks
α UMi	02 31 50.4	+89 15 51	2.02	0.60	Low amp Cepheid
α Per	03 24 19.3	+49 51 40	1.80	0.48	6 days
γ Cyg	20 22 13.5	+40 15 24	2.20	0.68	11 days
α Cyg	20 41 25.8	+45 16 49	1.25	0.09	> oscillation modes

Part Two

The Institute for Space and Terrestrial Science (ISTS), Dynacon Enterprises Limited and the University of Toronto propose that the MOST microsatellite mission be developed under the Canadian Space Agency's Small Payloads Program. MOST (which stands for Microvariability and Oscillations of STars) is a small space telescope. MOST will accomplish an important astronomical objective, gathering high-quality long-period stellar photometry data (measuring fluctuations in stelar brightness) for selected stars, from which stellar age, core composition, stability and presence of planets can be inferred. Because photometry places much less-stringent requirements on the telescope used than does imaging astronomy, this mission can be accomplished within the minimal mass, volume, power, data rate and cost resources available in a microsatellite mission.

This Part of the proposal outlines the design concept for the MOST instrument and its microsatellite bus, as well as the approach to developing and operating MOST. **Note:** Dynacon has provided a considerable amount of confidential material relating to their business plans to develop attitude control system products and microsat buses for part 2 of this proposal. Also, Surrey Satellite Technology Limited has provided detailed pricing information relating to their UoSAT microsat product. This information should be treated as confidential, and should not be released other than to reviewers of this proposal.

2.1 MOST Mission Overview

This section briefly summarizes the key features of the MOST mission, and explains how MOST relates to the objectives of the CSA's Small Payloads Program. The scientific objectives that MOST will achieve are summarized below in Section 2.2.1, and discussed in detail in Part One of this proposal.

2.1.1 The MOST Microsatellite

The MOST microsat, illustrated conceptually in Figure 2.1, will consist of two major components: the **instrument** and the **bus.** The MOST Instrument will consist of a small reflecting telescope, with an aperture of between 10 and 15 cm, which projects a narrow field of view (about 0.5° wide) star field image through a filter and beam-splitter onto a pair of CCD detectors. The image from one detector will be sampled rapidly and provided to star-sensor software to enable precise attitude control. A "windowed" segment from the second detector's image will be sampled (less frequently, to minimize readout noise) to measure the brightness fluctuations of a target star in the window. A
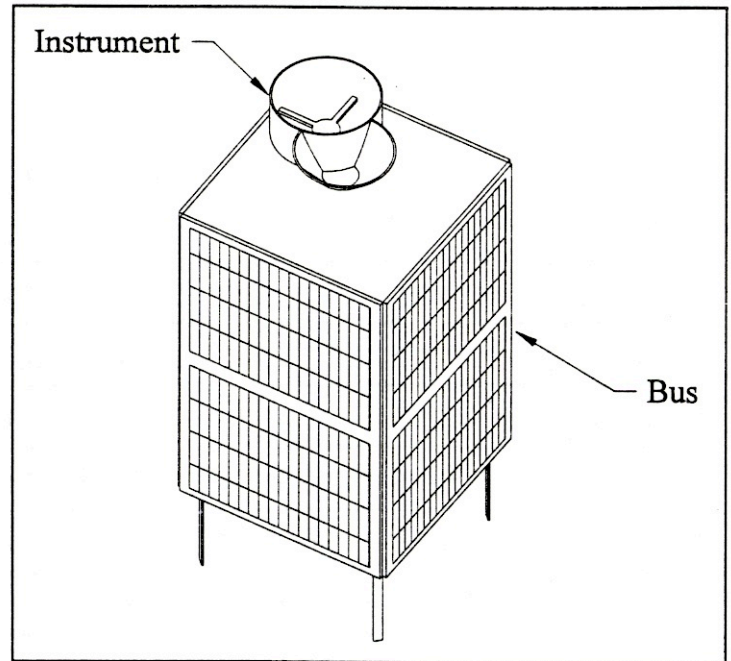

Figure 3.1: The MOST Microsatellite

passive thermal radiator plus trim heater will hold the CCDs temperature at about -50°C.

The MOST Bus will provide support functions to the telescope instrument. A structural frame will provide mechanical support. Solar arrays, batteries and power conditioning electronics will supply power. An attitude control system, described further below, will point the telescope in the desired direction. An on-board computer system will collect and process data from the telescope, and operate the other support equipment. Commands from a ground control station will be received by a command receiver, and science and engineering data will be sent to the ground by a telemetry transmitter.

At this point in time, no Canadian contractor has yet developed direct experience in building low-cost microsats. The MOST team views this as a challenge and an opportunity, to initiate a Canadian microsatellite program that incorporates the best features of the most successful microsat programs in other countries; MOST industrial team member Dynacon's strategy for doing this is outlined in Section 2.2.3. In the meantime, in lieu of a "CSA Microsatellite User's Handbook," the MOST team has relied on recent reference material such as WERTZ & LARSON, and direct contact with various microsat builders outside Canada, for data on achievable microsat capabilities versus constraints. Based on these, initial design work for the MOST spacecraft indicates that all these functions can be provided within the mass, power, volume and cost constraints typical of previous successful microsats. With a bus volume of about 95 litres, an instrument volume of about 30 litres, and a mass under 50 kg, this spacecraft will be compatible for launch as a secondary payload on a variety of popular launch vehicles.

2.1.2 High Performance Attitude Control: An Enabling Canadian Technology

Dynacon Enterprises Limited, the industrial contractor for the MOST bus, recently completed a CSA-funded study (reported in CARROLL ET AL.) into past practices, trends and technologies for attitude control for small spacecraft. Few microsatellites in the past were found to have achieved attitude pointing performance much better than 1° accuracy. Much improved microsat attitude control performance is technically feasible, but has been impeded by the lack of availability of miniature versions of some of the key components that are routinely used to achieve high performance attitude control (HPAC) in larger satellites (here, HPAC refers to pointing accuracies of 0.01° or better). In particular, very small and low-cost versions of high-accuracy star sensors, and miniature "reaction wheel" or "control moment gyro" torque actuators, are necessary components of a HPAC system for an affordable microsatellite—a collection of standard-sized versions of these components for some previous larger satellites could easily exceed the entire cost and instrument mass for the MOST mission! However, current technology development trends in several countries show that miniaturization of these components is technically feasible, and that commercial versions should soon be available. An order of magnitude or better improvement in microsat attitude control performance is widely expected within the next two years.

Because of this, and because of recent rapid growth in the international microsat market, Dynacon has identified a market niche for very small reaction wheels and control moment gyros. Dynacon has current experience with these types of actuators—they have developed and tested prototype, miniature versions of both actuator types for the CSA's DICE Space Shuttle microsat-based experiment. With CSA support, Dynacon is currently developing a vacuum-qualified version of their miniature reaction wheels suitable for use on other microsatellites. Working jointly with Surrey Satellite Technology Limited (SSTL, the commercial branch of the University of Surrey's eminent microsat program), a flight test of this design is planned for late 1997 on an SSTL microsat mission. SSTL has expressed great interest in the potential for Dynacon-produced miniature reaction wheels to enable SSTL to develop new markets, using versions of the standard microsat design equipped with Dynacon-provided HPAC subsystems.

The MOST microsatellite is a platform for an astronomical telescope, which relies on moderately precise pointing: pointing *accuracy* of about 0.2° with respect to the fixed stars, along with pointing *stability* of about 0.02° over a period of 100 seconds. This level of performance will allow MOST to achieve its basic goal of gathering photometric data from a single star at

a time. Based on initial analyses carried out in CARROLL ET AL., Dynacon reports that this level of performance is achievable, using the Dynacon reaction wheel design, and assuming availability of a suitable star sensor. Even better performance may be achievable, which could enable valuable extensions to the basic MOST mission, such as allowing simultaneous photometry from several target stars. A new study recently begun by Dynacon and SSTL (under contract from the CSA's Space Technology Development program's International Cooperation Element) will include refinements to the performance analysis reported in CARROLL ET AL., employing the spacecraft parameters from MOST; refined performance estimates should be available by mid-1997.

MOST will use Dynacon's miniature reaction wheels for attitude control actuation. In order to achieve precise attitude *sensing*, MOST will make use of an innovative approach: **the MOST instrument itself will be used as the primary attitude sensor.** The telescope will incorporate dual CCD detectors sensing identical images. One of those detectors will be sampled at a high rate to provide star-field images for processing by star-sensor software running on an on-board computer; a miniature star-sensor processing computer is being developed by Ottawa's CAL Corporation, and UTIAS is investigating enhanced algorithms for this function, with MOST as the target application. This approach will provide the most appropriate possible attitude reference for telescope pointing purposes, while avoiding the considerable expense and mass of an additional, dedicated star sensor-head. The redundancy inherent in the paired CCDs will also increase the reliability of the spacecraft.

ISTS believes that the advanced state of development of Dynacon's miniature torque actuators, the extent of existing CSA support for the development and commercialization of this technology, and the elegant simplicity of the science telescope-based star sensing, combine to result in a high level of confidence in the ability of the MOST microsatellite to affordably achieve the pointing performance level that its mission demands. By exploiting this technology for the MOST mission, Canada will be among the world's leaders in *using* the next generation of high-performance microsats, as well as in *providing* the components that enable them.

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2.1.3 Two Alternate Bus Development Approaches

Dynacon has identified two possible approaches to developing the bus for MOST:

- The first approach, **which has been chosen as the basis for this proposal**, is to develop a new microsatellite bus design, based on the system architecture used in the highly successful "UoSAT" series of microsatellites, which are built by SSTL. The design work will be carried out under Dynacon's engineering management, and will involve extensive student participation via design classes and thesis work at UTIAS. Wherever possible, existing Canadian suppliers of components and subsystems will be used. For example, CAL Corporation in Ottawa may be able to provide star sensor hardware for MOST, ComDev is developing miniature Command and Data Handling computer technology, and Dynacon is developing the miniature torque actuators that are needed. For this approach, contacts will also be made with the AMSAT organization for cooperation in developing communications, computer and power subsystems for MOST (most successful microsat designs, including SSTL's UoSATs, were developed with the help of AMSAT's experienced volunteers). **This approach, as documented below, is fully compliant with the terms of the SPP AO.**

- Dynacon has also identified a potentially attractive second approach to developing the MOST bus. This involves transferring to Canada the technology that forms the foundation for the University of Surrey's microsatellite program, which has become a *de facto* world standard for low cost, and high performance and reliability. Dynacon would gain access to this technology through their HPAC development partner, SSTL. This approach would involve a technology transfer license and some training (which Dynacon expects would be financed mainly by non-SPP funds), and would result in development of an on-going capability within Canada to build very low-cost and reliable microsat buses suitable for use in Space Science Branch (and other) missions. Dynacon is in the process of organizing the acquisition of that technology, as discussed further in Dynacon's accompanying letter of support. This could be a very attractive option for development of the MOST bus; however, since a technology transfer agreement has not yet been reached, this approach is included here as a separately priced option to the primary proposal, to be investigated further (if desired) during Phase A.

2.1.4 Phase A Functional Prototype Model

It is generally recognized that successful development of low-cost spacecraft requires a departure from the "standard" satellite development approach used for most large space missions in the past (this fact is the motivation for books such as WERTZ & LARSON, and has motivated many successes in the new "smallsat movement"). Dynacon and UTIAS have employed an "Early Prototyping" technique in the development of their DICE microsat platform, as a means to inexpensively gain early experience with and confidence in the design of a novel space system. For DICE, this involved including during Phase A an activity to develop "functional prototypes" (embodying the main functions, but not necessarily the final size, shape or materials) of the key DICE subsystems, and testing these both individually and integrated together. Some key DICE components and design features had the potential to greatly improve mission performance, but their behavior in combination with other system elements was both critical to mission goals, as well as difficult to analyze within the cost constraints of a Phase A study. Early Prototyping allowed these to be tested using rapidly-developed, low-cost hardware and software. It also helped to expose some serious issues with the original system design concept, early enough to allow these to be addressed via design changes with little cost impact, and provided a basis for estimating flight hardware and software development costs for DICE.

The MOST microsat design has several aspects that could benefit from this approach:

- The level of attitude control stability that is achievable by the bus is critically important in the selection of the size of the "target windows" that the instrument will use when integrating stellar brightness signals. This stability will be affected by numerous subtle attitude control sensor and actuator effects which will be difficult to analyze fully in Phase A

- The size of the instrument target windows will affect the choice of stellar targets, since a too-large window could include too many bright stars within it.

- The specification of acceptable attitude control accuracy will be affected by the extent to which wandering of the target windows around the detector's field of view introduces photometric errors due to detector mis-calibration, an effect that is difficult to analyze without tests of representative hardware.

During Phase A, in order to help develop confidence in the MOST schedule and cost estimates and risk assessments, a "Functional Prototype Model" (FPM) emulating several of the key MOST subsystems will be built by Dynacon, UTIAS and ISTS. These will include:

- The telescope, mirrors, filters, CCDs and CCD drive electronics.

- The reaction wheel set, and a set of solid state rate sensors.

- The on-board control computer, with star sensor, attitude control, instrument image processing and data management software.

- Telemetry to an off-board command computer.

- Telecommand and data analysis software for the command computer.

Some of these will be tested separately, after which all of this equipment will be integrated and tested together. For integrated testing the equipment will be mounted on a balanced, 3-axis air bearing to allow attitude control performance to be evaluated; this could be tested in an enclosure with a view of the night sky, to allow the instrument's star sensing and photometry functions to be evaluated while a representative attitude control system is operating. Testing in Phase A will aim at confirming the feasibility of the basic design concept for MOST; testing during subsequent phases will provide a testbed for rapid prototyping of designs for flight software.

UTIAS is currently in the process of developing a new spacecraft attitude control system testing facility, in support of Dynacon's reaction wheel flight test project. This will include an embedded control computer and battery-based power supply, along with a wireless modem high-speed command and telemetry link (all of which are DICE heritage), all mounted on a rotary air bearing. UTIAS also plans to develop representative reaction-wheel based attitude control systems, and test them using this facility. Initial financing for this will come from the University of Toronto's internal funds; additional funding has also been requested from ISTS. This equipment, along with a set of Dynacon-supplied reaction wheels, will provide the basis for the MOST FPM bus. ISTS (with the U of T's MOPITT lab) will develop the MOST FPM instrument hardware (using high-end astronomy-hobby-grade telescope and CCD hardware, which will be of adequate quality while minimizing costs) and software (which students will help to develop). The DICE prototype model took about 3 months to design and build from a standing start; with the DICE equipment and the UTIAS facility as a starting point, the MOST FPM will easily be completed within the 6 months of Phase A.

2.1.5 Public Outreach

The MOST team has identified an exciting approach to promoting interest in this mission among the general Canadian public, one that goes beyond the usual approaches to space project promotion (press releases, etc.). The help of the Royal Astronomical Society of Canada (the RASC, Canada's amateur astronomy organization, with 2800 members around the country organized into 23 regional Centres) will be enlisted to organize a **MOST Observing Contest** . Contest details will be established during Phases A and B; the current concept is that contestant teams, each comprising RASC members and high school students, would submit proposals (including target choice rationale and data analysis plans) for observing particular stars using MOST. A selection committee (including CSA, MOST team and RASC members) would select one or more winning proposals; after the set of primary MOST mission targets had been observed (by the current plan, about a year into the mission), MOST would be turned to observe the winning contestants' target, after which the photometry data would be returned to them for analysis. This contest will be run by the RASC, in cooperation with the MOST team and the CSA.

This contest would make a very large number of members of the public (RASC members and high school students) aware of the details of the MOST mission, as well as of the CSA's Space Science program in general. The contest also has a very strong potential for attracting the attention of the national news media. The potential for young people to be granted access to "command" the satellite carrying Canada's first space telescope will be very exciting to the students and their parents and teachers, which will make this an interesting "human interest" story. The RASC's across-Canada reach will give the story a national angle. The RASC and MOST team will participate in a series of media-friendly "news events," such as announcements of the contest opening, the winning team and the commencement and conclusion of that team's observations.

Information about MOST will be distributed by the RASC, via their **RASC Journal** publication, which has a circulation of about 3,000; this information would explain the basics of the MOST mission and spacecraft, as well as of astronomical photometry and astroseismology, to provide a basis for competing teams to create their proposals. Additional detailed information will be made available by the MOST science team members, via a MOST World Wide Web site. In addition to general descriptions of the MOST mission, spacecraft and status, this could grow to include science photometry data files, some of the microsat's engineering data, and reports on mission results.

2.1.6 MOST & the Objectives of the Small Payloads Program

The MOST team believes that the combination of the MOST mission itself, and the experienced team that will result from developing MOST, will meet *all* of the objectives listed in Section 4.3 of the "Small Payloads Program Backgrounder" document. In what follows, each of these nine objectives is addressed, in turn:

■ The MOST mission will be a low-cost microsatellite, developed within less than three years. In addition, the MOST bus development team (Dynacon and UTIAS) plan to develop a bus design that could provide a low-cost platform for future Space Science Branch microsat missions. This would meet the primary SPP objective of providing Canadian space scientists with low-cost, regular and rapid access to space to carry out experiments.

■ The MOST team plans to involve students extensively in bus and instrument development. Science team members will employ graduate students to aid in instrument design and test, software development and data analysis; this will help both ISTS and the University of Toronto MOPITT lab to maintain their in-house optical instrument development and test capabilities. Graduate engineering students at UTIAS will be actively involved in bus design, assembly and testing, through thesis projects, as well as through a new graduate-level spacecraft design course that UTIAS plans to run in support of MOST; this will extend the spacecraft design capabilities that UTIAS has been developing, and help provide a solid foundation for other possible future microsat development at UTIAS.

■ MOST industrial team member Dynacon Enterprises Limited, in conjunction with UTIAS, plans to develop a continuing capability to develop microsat buses, for use both by the CSA's Space Science and Space Technology branches, based on the design developed for the MOST mission. A proposal to that effect is under discussion between Dynacon and the CSA Space Technology branch.

■ MOST will result in considerable interaction and synergy between various university departments and industry. The Physics and Astronomy department at the University of Toronto will work jointly on instrument development and testing, under the ISTS Centre of Excellence. They will interact with the bus development team, with industrial team member Dynacon, and with the engineering graduate school department UTIAS.

■ The MOST mission will contribute in a most significant way to the on-going build-up of microsatellite development capability at Dynacon and UTIAS.

■ Dynacon is aiming to become an exporter of components and subsystems for microsatellite attitude control, starting with its miniature reaction wheel product. Development of this technology at Dynacon is being supported by cooperative research conducted by UTIAS—Dynacon was created with a goal of "spinning off" UTIAS capabilities in spacecraft dynamics and control into commercial products. Use of Dynacon's high performance attitude control system on MOST will help provide a "home market" advantage for this technology, which will help with selling this product into export markets.

■ CSA Space Technology personnel are already involved in Dynacon space systems development, including the DICE Space Shuttle microsat. Dynacon's intention is to use this same approach in developing the MOST bus, and ways and means of accomplishing this have been discussed with Space Technology managers. For example, Space Technology engineers may carry out on-ground tests of the MOST attitude control system, using the CSA's ODIN ACS testbed. In this way, MOST will provide a mechanism for Space Science and Space Technology branch personnel to work cooperatively.

■ The MOST team strongly endorses the Space Science Branch's goal of communicating the excitement and benefits of space science to the Canadian public. Because of the synergy between the MOST astronomy mission, and the enthusiasm and national scope of the RASC's amateur astronomers, MOST provides a unique opportunity to create a very low-cost but effective public outreach program to achieve that goal.

■ The MOST team plans to involve the international science community in this mission. An astronomer at the world-renowned Harvard-Smithsonian Center for Astrophysics has been enlisted as a member of the core science team. The planned approach to gaining a launch opportunity is to involve NASA scientists in selecting targets and analyzing data as well, in return for which there is a good chance that NASA will provide a secondary payload launch for MOST at no cost.

2.2 MOST Mission and System Description

The MOST team has carried out a considerable amount of initial design work, particularly related to the interaction between
● the mission's basic scientific objective
● the design of the telescope
● the selection of an acceptable orbit
● the availability of suitable secondary payload launch opportunities

- the functional design and layout of the bus and instrument
- the design and analysis of a suitably high-performance attitude control system
- the likely reliability/lifetime of the flight equipment
- the life-cycle cost of the mission. Some of the key results of this work are summarized in this section. While some of the details will undoubtedly change based on the more-detailed analysis and design work planned for Phase A, the general characteristics of the design presented here are expected to resemble closely those of the final MOST design.

2.2.1 Mission Requirements Definition

The design of the MOST system stems from the primary MOST mission objective: to gather astronomical photometry data from several different target stars, which when suitably analyzed will permit characterization of stellar variability over scales of minutes to weeks, with the signal/noise ratio (S/N) for coherent stellar modal pulsations exceeding 10^5 per mode (the goal being $S/N \sim 10^6$), and with a modal frequency resolution of 0.15 micro-Hz. This implies the following **top-level science requirement** for the MOST telescope instrument:

Equal time-interval (commandable between 0.1 and 100 seconds), broad spectral band observations of photometric variability of at least 6 bright (mag < 8) stars (with a precision per sample of between ±0.001 mag and ±0.003 mag, and an accuracy of between ±0.0014 mag and ±0.005 mag, the ranges representing dependency on absolute magnitude of the target star), over periods up to 6 weeks per target star.

This requirement has been carefully selected to be achievable by a simple, inexpensive instrument, one which furthermore is intended to be as compatible as possible with a low-cost bus design and a low-bandwidth, intermittent communications command and telemetry approach. A key element in the plan to avoid cost growth is that the MOST team is resolved to **make minor adaptations to the top-level science requirement** where appropriate during the development process, in response to the inevitable minor discrepancies between the originally-specified requirements and the initial bus and instrument design concepts that will be found as development proceeds, in order to minimize expensive equipment design changes. This is a continuation of the on-going evolution of the top-level science requirement during the development of this proposal, and will be done under the supervision of the MOST PI, to ensure that the final requirement retains its essential character and that the MOST microsat will be able to produce sufficiently valuable photometry data.

2.2.2 Mission Analysis

Orbit Selection: A key element of the MOST science requirements is the need to be able to keep a target star in continuous view, for viewing periods of up to two months. The ability to accomplish this is constrained primarily by the fact that the Earth will block out a large portion of the sky at any particular moment in MOST's orbit. The portion of sky blocked out by the Earth will vary as MOST travels around its orbit. An orbit must be chosen for MOST so that suitable target stars remain unobscured by the Earth for up to two months at a time. (While *all* stars will be viewable by MOST at *some* point in its orbit, most stars will "set" behind the Earth within half an orbital period, or about 45 to 50 minutes, of "rising.")

Fortunately, every Earth orbit has two "zones" of the sky that are unobscured by the Earth throughout the orbit; illustrated in Figure 2.2, these "Continuous Viewing Zones" (CVZs) are centered about the two vectors normal to the orbit's plane. The angular extent of these zones depends on the height of the orbit above the Earth, with higher orbits yielding larger CVZs. MOST will be used to observe target stars in the CVZ of its orbit; in order to include as many target stars as possible in the CVZs, MOST's orbit will be chosen to be as high as possible. In order to avoid the radiation environment of the inner Van Allen belt (which would require the use of expensive, radiation-tolerant electronics on MOST), an upper altitude limit of about 900 km is imposed. This corresponds to a maximum CVZ diameter of about 58°.
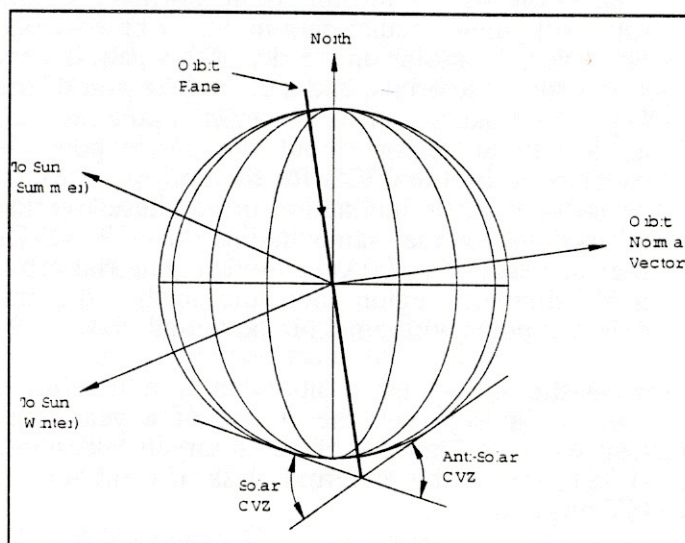
Figure 2.2: Continuous Viewing Zones for Radarsat Dawn/Dusk, Sun-Synchronous Orbit

The plane of most Earth orbits changes with time, due to "nodal precession" caused by Earth's non-spherically-symmetric gravitational field (as well as other, much smaller effects). The effect of this is that an

orbit's normal vectors, and hence the centroids of the CVZs, will "scan" along a closed, circular path when projected onto the celestial sphere. The radius of this path, and the rate at which the orbit normal traverses the path, depend on the orbit's inclination and altitude, as well as its eccentricity (if non-circular). Thus, the size of the CVZs for MOST, and the rate at which those viewing zones scan across the sky, will be determined by the choice of orbit altitude and inclination. This will in turn determine which target stars will be continuously viewable by MOST, and when continuous-viewing windows will open and close for each target.

Two classes of orbits match the MOST two-month target viewing requirement:

- **Near-Polar Orbits:** The orbit nodal precession rate (due to Earth gravity perturbations) for an orbit with a 90° inclination is zero—the CVZs for such an orbit will not move with respect to the celestial sphere, and hence all stars in those CVZs would remain perpetually in view (if not for other, smaller sources of orbit perturbation). For orbits with inclinations close to 90°, the CVZs drift at a rate slow enough to allow stars to remain in the CVZs for several weeks. Higher altitude helps in two ways here, both by increasing the size of the CVZs and reducing their drift rate (at a given inclination), both of which increase target star dwell time in a CVZ.

- **Near-Equatorial Orbits:** Orbits with lower inclinations suffer the highest orbit nodal precession rate, with the orbit normal vectors traversing their circular path in only 7 or 8 weeks. However, the radius on the sky of this path is very small for these orbits, and a circular region of the sky about Polaris at the north celestial pole (as well as a similar region about the south pole) is overlapped by the CVZs for the entire precession period—for a 0° inclination orbit, these overlap regions have the same radius as the CVZs themselves. For a 900 km altitude equatorial orbit, a 58° diameter region about the north and south celestial poles will remain in perpetual view.

Because the near-polar orbits scan a much larger portion of the sky over the course of a year, they maximize the total number of stellar targets accessible to MOST; this is the preferred class of orbit for the MOST mission.

A secondary constraint on the orbit of MOST is that the Sun must not come close to being in the field of view (FOV) of the telescope—inside the telescope's FOV this would saturate the CCD detectors, and inside the FOV of the CCD passive cooling radiator it would overheat the CCDs and reduce their signal/noise ratio unacceptably. A particularly attractive orbit from this perspective is a *dawn/dusk sun-synchronous orbit*, for

which the precession rate is precisely one revolution per year, and the Sun remains always close to one of the orbit's CVZs. For this type of orbit, the telescope can observe using the CVZ opposite the Sun's direction, in which case the Sun never comes within 90° of the telescope's FOV, allowing the size and mass for light-baffles for the telescope and its passive thermal radiator to be minimized. (This also has positive effects on the design of the overall spacecraft power system, since this type of orbit does not experience eclipses at all, except during the summer months, and then only brief ones.)

Launch Options: Almost all microsatellite missions are launched as secondary payloads from a large launch vehicle, in order to avoid paying the >$10M cost of a dedicated launch; CSA Small Payload Program microsatellite missions will almost certainly follow this strategy. However, as a result secondary payloads must accept the orbit parameters that are chosen for the primary payload. To launch MOST, a primary payload launch must be found with suitable secondary payload *capacity*, going into a suitable *orbit*, with a suitable launch *date*. Given the proposed MOST development schedule, a launch in 2000 would give the MOST system enough time to be built, without leaving too long a slack time between then and launch.

Many primary-payload spacecraft are launched into polar or near-polar orbits, as these are ideal for Earth observation and communications-constellation purposes. These launches are conducted for customers such as NASA, ESA and the Japanese space program, using the Delta, Ariane, Proton, H-2 and other launch vehicles; many launches are also expected in the 2000 time-frame for Motorola's Iridium network and other similar commercial customers. A variety of secondary payload opportunities is anticipated for any given year, which will yield a range of orbits with a CVZ size and scan rate close to the MOST requirements. However, relatively few launches are carried out into low equatorial orbits, and few secondary payload opportunities are expected to be available for these. On this basis, a near-polar orbit will maximize the chance of MOST finding a suitable launch opportunity.

The primary constraint on the choice of launch for MOST is the suitability of the orbit. A strong secondary consideration is the *cost* of the launch. In order to reduce the launch cost (estimated at US$1M), the MOST team recommend that NASA be requested to sponsor the MOST mission in return for NASA participation in the experiment (e.g., by granting access to NASA-designated astronomers to use the MOST telescope for observing). **The MOST science team is entirely willing to welcome NASA scientists onto the team.**

Baseline Launch Opportunity–With Radarsat 2: The CSA is tentatively planning to launch the Radarsat 2 mission in the year 2000. Current plans appear to favor using the same launch vehicle and orbit as Radarsat 1: a Delta II launch provided by NASA, into a 785 km altitude dawn/dusk sun-synchronous orbit. This would be a very good orbit for MOST; not only does it have the desirable dawn/dusk sun-synchronous characteristic, it is also at almost an ideal altitude. At 785 km the effects of Van Allen belt radiation are quite low, the size of the CVZ is quite large at about 26° radius, and the CVZ scan rate is at the ~1°/day sun-synchronous rate, resulting in target star dwell times of as long as 7 weeks in the CVZ. For this reason, the Radarsat 2 mission has ben selected for the purposes of planning the MOST mission. (If a different launch is eventually selected for MOST, some of the details of the design proposed here may have to change, but the basic approach should remain useable.)

The MOST team has contacted the NASA Headquarters Secondary Payloads manager (Karen Poniatowski). NASA is currently assuming, for planning purposes, that they will be providing the Radarsat 2 launch to the CSA on a Delta II launcher, under an arrangement similar to the Radarsat 1 launch. Unless Radarsat 2 experiences weight growth (the current plan is for minimal spacecraft modifications relative to the Radarsat 1 design), there should be secondary payload space available on the launcher. According to NASA, no other secondary payload launch request has yet been made for this launch. A Delta II Secondary Payload User's Manual, including a launch provision request form, has been forwarded from NASA to the MOST team. Filling in and submitting that form will begin the launch manifesting process, including a decision regarding whether NASA scientists recommend that NASA sponsor the MOST secondary payload; the American member of the MOST team, a prominent astronomer at the Harvard-Smithsonian Center for Astrophysics, is prepared to lobby NASA to agree to sponsor MOST. According to NASA, matching a secondary payload against a launch vehicle is done about 30 months prior to launch, which fits the MOST schedule.

Designing the MOST microsat to rely on the characteristics of a dawn/dusk sun-synchronous orbit can produce an attractively simple satellite design. A concern was raised that, if the plane of this orbit drifted (from the dawn/dusk plane towards noon/midnight) due to natural perturbations or errors in initial placement by the launcher, then satellite performance (e.g., solar array power collection) could degrade with time. To address this issue, a launcher orbit dispersions analysis and a drag analysis has been carried out for MOST in this orbit, to determine the extent to which the CVZ precession rate is expected to drift from its ideal, sun-synchronous value due to errors in initial orbit injection by the launch vehicle, and due to altitude decay resulting from atmospheric drag (unlike Radarsat,

MOST will not have thrusters with which to combat these effects). Worst-case drag and 3-sigma launcher dispersions result in an orbit plane drift rate error of about 2°/year, which would not negatively impact the MOST satellite's performance significantly for several years after the primary one-year mission is completed. On this basis, the Radarsat 2 launch opportunity appears able to provide MOST with an ideal initial orbit with excellent stability characteristics.

Attitude Control Modes: The choice of a dawn/dusk sun-synchronous orbit for MOST would allow the basic set of attitude control modes to be fairly simple, minimizing the total amount of attitude control hardware required while retaining robustness:

- Immediately after launcher separation MOST could use magnetorquers, driven by magnetometer signals ("B-dot" control) and/or signals from attitude rate sensors, to eliminate any separation-induced tumbling motion.

- Then, either interpretation of magnetometer signals via an on-board orbit propagator, or signals from a set of sun-sensors, would be used to derive commands to point the MOST telescope boresight in the anti-solar direction. This should be able to establish boresight direction with an accuracy of about 1°. Also, these first two modes together could provide the basis for a contingency "safe-hold" procedure.

- The science telescope could then be used to acquire a reference star-field image, and then gather subsequent images which would be used to generate commands to inertially "freeze" the microsat's attitude in that initial reference direction (using reaction wheels to generate primary control torques, and using magnetorquers to desaturate the wheels). The reference image would be downloaded to the ground, for manual registration against celestial coordinates. (Alternately, a more-complex, autonomous star sensor could perform this function entirely on-orbit.)

- Commands from the ground would be used to periodically re-target the telescope boresight reference direction, via a series of slew maneuvers. Between slews, the ACS would hold the attitude "frozen" in the reference direction, for periods as long as two months per target.

2.2.3 System Design Approach

Developing a microsatellite to meet the $4M cost constraints specified in the SPP AO will be challenging. It is certainly *possible* to build a microsat within this constraint; three examples (AO-13, AO-16 and PoSAT-1) are presented as case-studies in WERTZ & LARSON. The first two of these were AMSATs, built with extensive volunteer labor (reducing costs by 90%),

while the third was build commercially by SSTL, who charged about CDN$3M for developing and launching PoSAT and providing and running a ground station for 1 year (internal costs of the PoSAT consortium not included). Most non-volunteer microsat vendors usually charge a price considerably higher than this; SSTL is almost unique among microsat vendors in their ability to achieve such low costs.

Dynacon has closely studied the SSTL design approach, in order to learn to apply their low-cost, high-reliability approach to the MOST mission; this has been done via reviewing publications such as WERTZ & LARSON, visiting SSTL on a fact-finding tour, and subsequently meeting with senior SSTL designers and managers (these in turn have led to the Dynacon/SSTL HPAC work described in Section 2.1.2—in a sense, the first industrial spin-off from the SPP!). An important factor in SSTL's ability to achieve high reliability at a low per-mission cost is their re-use in each mission of many design elements from their existing modular bus design, which in turn gradually evolves via a program of test-flying new components and subsystems. The very close working relationship between SSTL and the University of Surrey (from which SSTL was "spun off") provides SSTL with access to University resources, which are used to research and initially develop new design elements. Because they launch new missions frequently, it costs SSTL less to evaluate new component via test-flight, than it would to carry out "the usual" extensive (and expensive!) ground-based analyses and tests. By this means, SSTL has evolved a very capable, flexible and modular microsat architecture.

Based on this analysis, Dynacon has adopted two complementary strategies to develop the MOST bus within the SPP cost constraints:

- The first is to **team with UTIAS to develop the MOST bus**. There is considerable similarity between the Dynacon/UTIAS relationship and the SSTL/U. Of Surrey one—both involve university departments which embody national centers of excellence in specific areas of spacecraft engineering research and training, and each company was "spun off" in order to commercialize research results from its parent university department. Dynacon has a long history of working closely with UTIAS on system development projects, including the current DICE Space Shuttle microsat project for the CSA; MOST will continue this collaboration.

- The second is that, rather than starting with a "clean sheet of paper" approach, **the MOST system architecture and bus designs will be based on the proven SSTL UoSAT system design**, which in turn was modeled after earlier AMSAT hardware and software designs and operational concepts. This design approach has been proven to be able to be implemented in a low-cost fashion, and to be able to result in a reliable microsat capable of a multi-year lifetime in orbit. The UoSAT design approach is able (when augmented with Dynacon's planned HPAC subsystem) to meet the requirements of the MOST mission, and following this approach will allow bus, mission, ground station and ground support equipment design costs to be minimized.

The MOST system design approach began with these as its axioms. When the science objectives of MOST were first being conceptualized, they were selected to be able to be accomplished using a HPAC-equipped UoSAT bus, with satellite operations conducted through a standard intermittent-contact SSTL ground station at standard SSTL packet-communications data rates. This was followed by initial design work, which was carried out to validate the feasibility of this conceptual mission. An initial instrument design was developed, specifying its functions, basic layout and major components. This was done in conjunction with an initial bus design, which used SSTL's standard UoSAT bus subsystem modules as a starting point, and proceeded by specifying changes that would be needed to support the MOST instrument and mission operations concept. SSTL was consulted several times during this process, to confirm that planned modifications were consistent with the basic UoSAT design. The resulting instrument+bus combination fits within the volume, mass and power envelope of a standard UoSAT mission, resulting in high confidence that the design is technically feasible to accomplish.

As mentioned in Section 2.1.3, this bus development approach could be brought to fruition in one of two possible ways. The first is to *develop a new bus design*, that would embody as many as possible of the design principles of the UoSAT system design. The second is to *transfer the UoSAT technology from SSTL to Canada*, then to build the MOST bus using SSTL's detailed designs and development methodology. The MOST satellite design presented here is consistent with both of those approaches.

There is an important interface between *system* design and *mission* design, in that the orbit selection has a primary effect on the resulting solar aspect angles, and on solar and Earth albedo heating of the satellite. The tentative selection of a dawn-dusk sun-synchronous orbit for MOST provides both an adequate orbit from the perspective of prolonged target visibility, as well as (with one spacecraft face always towards the Sun) a benign thermal control and solar power collection environment. A significant aspect of the MOST mission is that its attitude set-point (namely staring in an inertially-fixed direction) is necessarily different from that of the microsats that SSTL has built in the past (i.e., pointing towards the center of the Earth). This will necessitate some changes in the UoSAT bus design for MOST, in the approach to solar power collection and thermal control.

2.2.4 Instrument Design

The main function of the MOST instrument is to make continuous observations of the brightness of a specified star, keeping errors and noise to the lowest level possible, compatible with the need to keep instrument cost, mass, power consumption and volume within the following constraints

- development cost < $750K
- mass < 15 kg
- volume < 30 litres
- power consumption < 8 W
- on-board computation requirements compatible with a TMS320C25/30 transputer processor pair. (The mass, power and volume allocations were established based on the advertised instrument capacity of SSTL's UoSAT bus, and SSTL has flow the cited transputers successfully.) The basic design chosen is a small reflecting telescope with a narrow field of view, which collects image data using a CCD detector, and digitally processes that data on-board the satellite to extract periodic estimates of stellar brightness. Key features of the design are: The telescope will have an aperture of between 10 and 15 cm (final choice to be made during Phase A), with an effective focal length of about 200 cm, and a field of view of about 0.5°.

- The science data will be collected by a CCD, whose resolution is tentatively chosen at 1000 by 1000 pixels. Two of these CCDs will be included, each

Figure 2.3: MOST Instrument Layout
(Segmented View)
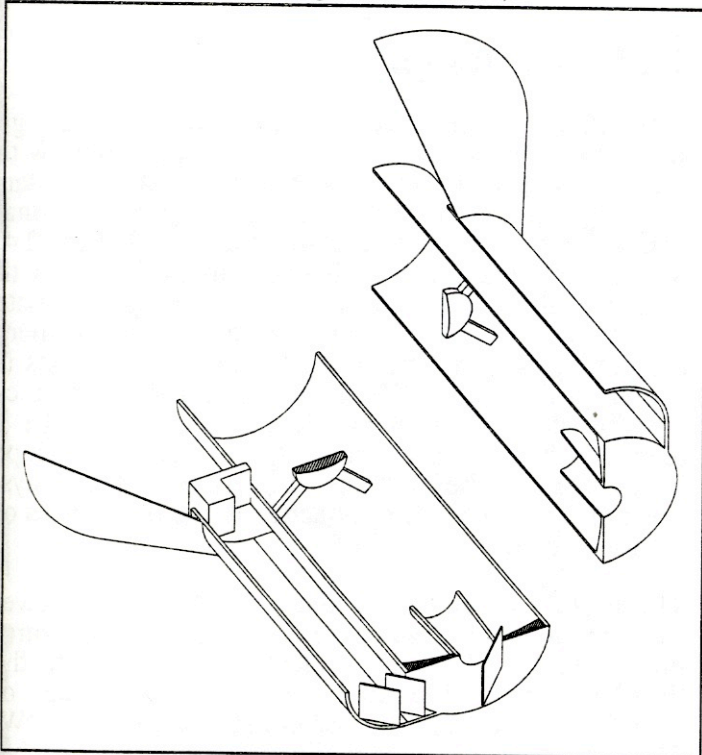
one capable of being sampled at an interval whose length is adjustable between 0.1 and 100 seconds (high sample rate images will drive the attitude control star sensor software, while low sample rate images will be used for science data due to their lower level of readout noise per pixel. Moderate-cost commercial astronomical grade detectors should be sufficient for MOST; sensitivity and saturation level will be chosen to be consistent with the brightness of the target stars and the planned exposure lengths, to achieve good signal/noise ratios.

- CCD temperature will be maintained at a low level (as low as -50°C) by mounting them on a cold plate, cooled using a passive thermal radiator. A small electrical heater will be mounted on the cold plate with a temperature sensor, which will be used to regulate the plate (and hence CCD) temperature within a narrow range to avoid temperature-dependent alterations in the scale factors of the CCD pixels.

- The optics will include a standard astronomical filter and a beam splitter. Beam splitting could be done by either a semi-transparent mirror, or alternately by a spectrally-dividing dichroic mirror; the latter option could allow MOST do provide some data on spectral dependency of stellar brightness fluctuations. This choice will be made in Phase A after further study of costs and potential science benefits.

- Small areas of the CCD detectors between the pixels are not sensitive to light, and if a sharply-focussed star image fell onto one of these areas the instrument would incorrectly register a decrease in the star's brightness. To minimize this effect, the MOST telescope optics will be deliberately "appodized", smearing out the image of the target star in a controlled way over several detector pixels. The instrument image processing software will combine readings from these pixels to arrive at a total star brightness estimate.

- The instrument will include the electronics to drive the CCD detectors, which will be designed to minimize detector readout noise. These electronics will in turn be commanded by an on-board computer in the MOST bus. This computer will receive the CCD output image data from the

Instrument Component	Mass (kg)
Primary Structure the Target Star's	3
Main Mirror	0.5
Secondary Mirror	0.1
Internal Baffle	0.25
Mirror Supports	0.5
Beam-Splitter	0.1
Filter	0.1
CCD Detectors	0.1
CCD Passive Thermal Radiator	1.5
CCD Controller Electronics Board	0.75
Wiring Harness	0.5
TOTAL	**7.4**

Table 2.1: Payload Mass Budget

instrument electronics, and will process it to extract star brightness data, and satellite attitude data. The on-board computer is considered part of the MOST bus, but the instrument-related software is considered to be part of the instrument.

■ The MOST attitude control system will maintain the target star within the field of view of the detectors. However, the target is expected to wander somewhat within that FOV, perhaps as much as 0.01°, equivalent to 20 detector pixels. The attitude estimation function of the MOST bus will estimate the location of the target star within the CCD; commercially available star sensors can accomplish this to within 0.003°, or about 7 detector pixels, and Dynacon/UTIAS are planning software enhancements that could reduce this error to 1 detector pixel. The instrument image processing software will command the pixels in a "window" immediately surrounding the target star to be sampled at a rate appropriate to estimate.

■ The MOST bus attitude control system is required to keep the location of the centroid of the target star within the boundary of the star's sampling "window" on the detector, for the duration of each sample period (which could range as high as 100 seconds). A window as wide as 0.05°, or 100 pixels, should be able to produce adequate science data (to be confirmed by detailed analysis in Phase A); the MOST attitude control system performance is expected to achieve much better stability levels than this, resulting in high confidence that the planned approach to tracking target stars and measuring their brightness is technically feasible using the MOST microsat design.

The above summarizes the *baseline* design of the MOST instrument, which ISTS is confident can be developed within the budget presented below. This is the simplest possible design that can achieve the mission requirements. In addition to this design, several possible design enhancements have been considered for the instrument. These would extend the scientific usefulness of the data collected, and could be considered for addition to the baseline design during Phase A, if refined budget estimates indicate their affordability. These include:

■ Addition of more CCD detectors along with more partly-reflecting or dichroic mirrors and appropriate filters. These could allow simultaneous brightness measurements for target stars in several spectral bands.

■ The baseline instrument design poses the minimum possible requirements on the bus attitude control system, by planning on gathering data from only a single target star at a time, which assumes the data-sampling window on the detector to be quite large. If, as it seems, better attitude control performance than this turns out to be achievable (to be confirmed in Phase A), then photometry could be done for multiple simultaneous targets using many smaller windows. This would significantly increase the volume of valuable data generated by MOST, for example by allowing photometry of multiple targets in stellar clusters.

The internal layout of the MOST instrument is illustrated in Figure 2.3 (an external view is provided in Figure 2.5). It comprises the components listed in Table 2.1, for which individual masses are estimated. Average power consumption for the instrument is estimated at under 4 W.

2.2.5 Bus Design

The MOST bus has been assumed to have a design similar to that of SSTL's UoSAT microsat bus, with suitable modifications to adapt this bus to MOST's star-pointing attitude control mode. The main functional components of the bus are illustrated in Figure 2.4, which shows the interfaces between them. The bus will be physically configured as a cuboid of approximate dimension 33×33×53 cm, with the instrument projecting through one face; the layout of the bus is shown in Figure 2.5. The batteries and all electronics will be mounted in stackable modular trays. The 4 reaction wheels (3 prime plus 1 spare) and the telescope instrument will be mounted above the stack of trays. Solar array panels will be attached to the outer faces of the assembled bus.

The current assumptions about the mass and power consumption of each subsystem are based on the figures published by SSTL in WERTZ & LARSON for the PoSAT design, which had a bus+instrument mass of 49.8 kg and average power consumption of 18.3W. These numbers were then adjusted to reflect a number of variations between the PoSAT and MOST bus designs:

- The PoSAT gravity gradient boom and tip mass (estimated at 5 kg) will be deleted, as MOST will not be Earth-pointing. Four reaction wheels of 1 kg each will be added, plus 1 kg of attitude rate sensors will be added (thus no net mass change for ADCS). All other PoSAT ADCS components will be retained.

- The longest eclipse duration for the dawn/dusk sun-synchronous orbit chosen for MOST is less than 15 minutes, one-third of the PoSAT eclipse duration. This will reduce battery mass required; PoSAT has about 10 kg of batteries, which could be reduced by perhaps 5 kg. It will also reduce the fraction of solar array power which must be used for battery charging, which could increase MOST's average consumable power available from PoSAT's 20W, to about 30W.

- The MOST reaction wheels will each consume an estimated 2W, adding 6W to the ADCS average power requirement.

- The MOST structure mass is assumed to be 1 kg larger then that of PoSAT, to provide reaction wheel and instrument support.Assume that MOST will have 0.5 kg of thermal control equipment (e.g., MLI blankets), to compensate for its sun-facing orientation.
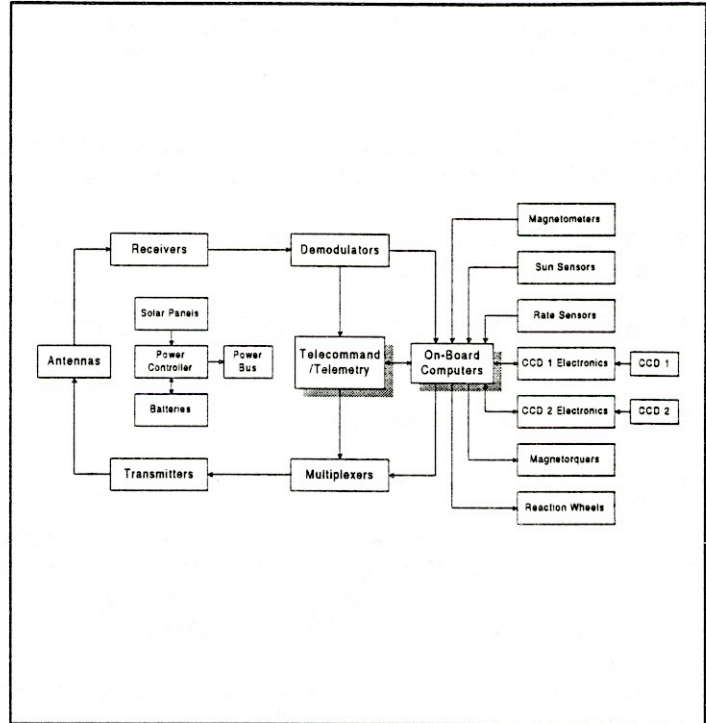
The resulting MOST total mass is 48.0 kg, and average

Figure 2.4: MOST Bus Functional Architecture

power consumption is 20.3W; a mass and power breakdown is provided in Table 2.2. These values are consistent with what was achieved for PoSAT, confirming the feasibility of the bus design approach.
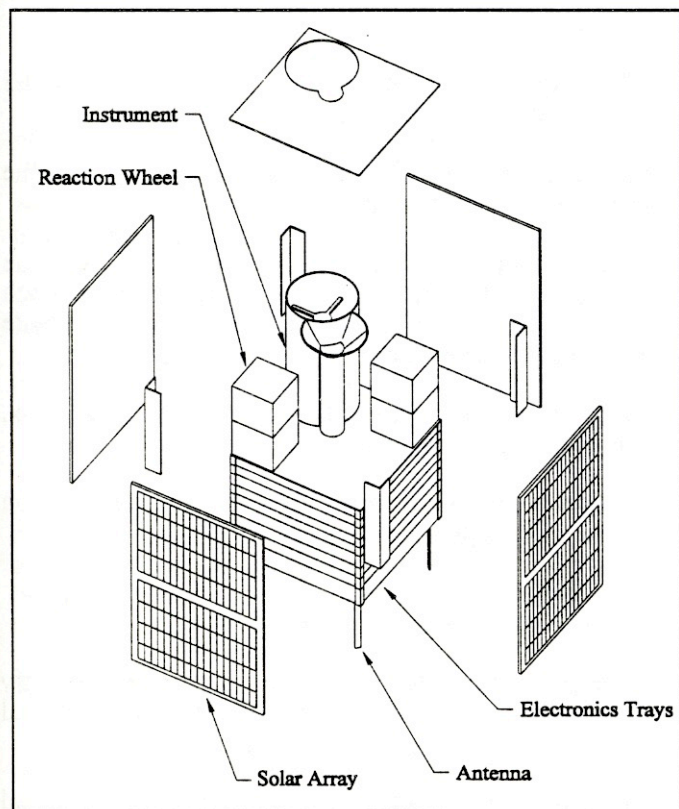
2.2.6 Ground Segment Design

The MOST Ground Segment comprises the **Ground Control Station** (which will send commands by radio to the MOST microsat, and receive telemetry in response), and the **Ground Support Equipment**

Figure 2.5: MOST Bus Layout

Table 2.2: MOST Microsat Mass Budget

Bus Component	Mass (kg)
Mechanics and Structure	7.9
Power System	11.5
Telemetry and Command System	5.6
Attitude Determination/Control System	10.5
On-Board Data Handling System	3.1
Thermal Control System	0.5
Wiring Harness	1.5
(Payload Total)	7.4
MICROSAT TOTAL	**48.0**

(which comprises all additional hardware and software developed to support the integration, testing, transport and launch of MOST).

The Ground Control Station design will be based on the standard SSTL ground station. It will comprise:

- An uplink radio transmitter (SSTL standard is 140-150 MHZ (VHF)).

- A downlink radio receiver (SSTL standard is 400-435 MHZ (UHF)).

- A small tracking antenna.

- A communications switching unit.

- Several (nominally 4) PC-type computers running software to control the tracking antennas, submit commands for transmission, decode telemetry signals, and archive the telemetry data.

With this design, about 750 kBytes of data can be received per satellite pass. The specified sun-synchronous orbit produces the equivalent of 4 high elevation angle passes per day over the ground station (one at 6 AM and one at 6 PM), yielding a data downlink throughput of 3 Mbytes/day. This is ample, as nominal MOST science operations (one observation every 10 seconds for one target star) will produce about 35 kBytes of data to be downloaded per day. The ground station will be mostly-autonomous, staffed for routine operations by one person 8 hours per day.

Various elements of ground support equipment (GSE) are expected to be necessary for MOST, including:

- Clean-room compatible shipping containers for the bus and instrument, and for the integrated satellite.

- Test support equipment to simulate the instrument electrical and data functions, to allow stand-alone functional testing of the bus.
- Similarly, bus-simulation electrical and data test support equipment to exercise the instrument during stand-alone functional tests.

- Instrument and bus test support rigs, for thermal/vacuum, launch loads and vibration tests.

- A solar-array simulation power supply, for supporting partial bus functional tests during development; this may also be used during final pre-launch functional tests.

- Equipment to produce and transmit uploaded command sequences, and receive and process downloaded telemetry data, during ground tests. This may include RF signal generators and receivers, emulating those in the ground station, to allow ground tests to exercise as much of the end-to-end communications equipment on the bus as possible, interfaceable to the input of the satellite's receiver(s) and the output of its transmitter(s). (This will likely employ much hardware and software in common with the ground control station.)

The requirements for these and any other elements of GSE will be defined as part of the process of generating the MOST Test Plan and Operations Plan. Some of the design may be carried out by CSA personnel; plans for allocating this work between CSA and the other team members will be decided during Phase A.

2.2.7 Testing

The MOST instrument and bus will both be thoroughly tested throughout the development process, both separately and after being integrated together. Some of that testing will be similar to that done for any small satellite:

- Extended, integrated functional test to verify integrated spacecraft functionality and provoke "infant mortality" failures on the ground rather than in space.

- Integrated structural tests (launch loads, shock and vibration testing, including a modal survey).

- Integrated thermal/vacuum tests to verify thermal model predictions.

- EMC testing, and testing of antenna radiation patterns.

- Magnetic grooming tests to minimize residual magnetic moment.

In addition, there will be tests that are specific to the MOST bus and instrument:

- Calibration ("flat-fielding") testing of the instrument, to determine the scale factor of each pixel of each CCD at one or more cold-plate operating temperatures.

- Alignment testing of the instrument's field of view, for both detectors.

- Optical testing to confirm the point spread function of the telescope.

- Thermal vacuum testing of the instrument, to verify thermal design of the detector's passive thermal radiator.

- Bus and instrument subsystem-level functional testing.

- If suitable facilities are available (e.g., possibly the CSA's ODIN ACS testbed), performance testing of components of the CAS (or perhaps the entire ACS) could also be done.

The facilities that could be used for this testing are specified in Section 2.3.6, below.

2.2.8 Mission Operations

Following final testing of the spacecraft in Canada, **mission operations** will commence with the transport of the MOST microsat and its ground support equipment to the launch site (if with Radarsat 2, this will be the Vanderberg launch site in California). The schedule and nature of the launch campaign is mainly dictated by the launch vehicle provider, as is the required role of a secondary payload team in that campaign. The main elements of the campaign are expected to be:

- Integrate all microsat elements, and check out using GSE.

- Integrate the microsat with the launch vehicle, and conduct final integrated testing and battery charging.

- Participate in required range tests (e.g., EMC testing with respect to on-board radios), and practice count-downs.

Shortly after the launcher places the primary payload in orbit, the MOST microsat will be released. This will trigger autonomous on-board processes to stabilize the microsat's attitude, begin battery charging using solar arrays, collecting data for telemetry transmission, and monitoring the receivers for commands. Within 12 hours of this time MOST will make a pass over the ground station, which will initiate the first **satellite commissioning** operations. Commands will be sent during this pass to the microsat to request a telemetry download; following the standard SSTL approach, this will likely also involve uploading the most-current bus and instrument operating software.

A period of (probably) several weeks will follow, during which all on-board systems will be tested out, and any necessary fixes to the operating software will be developed and uploaded. Once MOST's attitude control system has achieved stable inertial pointing, the corresponding reference star field image will be downloaded, and from this a set of slew commands will be developed and uploaded to acquire the first target star. After this, routine science operations will involve downloading photometry data files on each pass, along with engineering telemetry. Analysis of telemetry will be done on an on-going basis to monitor the health of all MOST systems.

On receipt of the science data files, the MOST science team members will analyze the data, and eventually publish the results of their analyses. After the primary science objectives have been met, observations of a secondary set of stellar targets will begin, including target(s) chosen via the Public Outreach contest. This will continue for as long as the MOST microsat remains healthy. Primary science operations are expected to be complete after 1 year; based on previous SSTL experience, and likely MOST orbit perturbations, observations may be able to continue for several years.

2.3 MOST Implementation Plan

This section summarizes the approach by which the MOST team will develop the MOST bus, instrument and ground segment equipment.

2.3.1 System Development Overview

The hardware and software that comprises the equipment to be developed for the MOST mission is partitioned into the following system *elements*:

- The *bus*
- The *instrument*
- The *ground station*
- The *ground support equipment (GSE)*

The work at the beginning of the development program will focus on the system as a whole. At the beginning this will involve defining the requirements and characteristics of the overall system.. Next, the focus will change to the lower (element) level, with detailed design and building of the individual system elements. Finally, the work will again rise to the system level, involving integrating, testing and operating the system. In this section, the activities to be carried out at the *system level* during each phase of the development program are summarized.

Phase A: Mission Definition and Planning

- Mission analysis and science requirements definition will be carried out in a coordinated manner, comparing target star locations and expected brightness variations with the viewing-zone motion characteristics for the orbits of various launch opportunities. This will result in a launcher selection, and selection of primary target stars, as well as defining instrument sample-period and saturation levels.

- System-level design will be carried out, specifying the basic requirements of all the system elements. This will include allocating mass, power and data processing resources to the instrument and bus subsystems, sizing the solar arrays and batteries, sizing the reaction wheels, defining the uplink and downlink RF frequencies and data rates, etc. It will also include defining the functions to be carried out by the ground station, and by the ground support equipment, and the interfaces between these and the other elements.

- A Functional Prototype Model (FPM) will be developed for the main bus subsystems, the instrument and the ground station command computer, including the basic instrument optics and detectors, and the attitude control system sensors, actuators and control computer. It will also include telemetry and telecommand via a wireless modem, allowing the prototype spacecraft elements to communicate with the prototype ground station computer. Software implementing the main functions of both flight and ground computers will be coded and tested. To the extent possible, these subsystem prototypes will be integrated, and tested while operating together. The FPM instrument will be built by ISTS and the MOPITT lab, and the FPM bus components and command computer will be built by Dynacon and UTIAS based on DICE prototype equipment; Dynacon and UTIAS will integrate the complete FPM.

- Planning will be done to finalize the details of teaming arrangements and financing from non-SPP sources, and to specify the technical and management approaches, risk issues, schedule and budget for the remainder of the project in detail. Project management, documentation and meetings will also be significant activities.

Phase B: Design

System-level work during this phase will mainly involve coordinating the design work between the system elements, and conducting a PDR and CDR for the system. Other activities will include project management, documentation and meetings.

Phase C: Manufacture, Integration and Test

- After the system elements have been assembled and tested individually, the bus and instrument will be integrated together, and tested in combination with the GSE, and with the ground station.

- Integrated functional testing of the spacecraft will be carried out. This will involve operating the spacecraft subsystems for extended periods of time, exercising the telecommand and telemetry subsystems by uploading and downloading data, etc. It may involve an extended functional test in a facility such as the CSA's ODIN ACS testbed.

- The instrument and bus will be brought together and integrated under clean-room conditions, either at the MOPITT lab or at CSA's DFL; the MOPITT lab may be used to carry out initial thermal/vacuum testing of the integrated satellite. If sufficiently clean conditions can be maintained at the CSA's ODIN testbed, then integrated functional testing may be conducted there. Following this, further environmental tests will be carried out at DFL. The CSA will likely lead this activity, with support from Dynacon and ISTS.

- Training of flight operations personnel will begin during this phase, an activity likely to be led by CSA.

- Other activities will include project management, documentation and meetings.

Phase D: Launch Support

This will involve integration and testing of the satellite at the launch site, integration of the satellite to the launch vehicle, final checks of the satellite's functions and its communications equipment via the GSE, etc. This will be led by the CSA, with major Dynacon support. In addition, development of the uploadable portion of the instrument and bus flight software will continue during this period. Other activities will include project management, documentation and meetings.

Phase E: Flight Operations

- After launch, the MOST satellite will go through a commissioning period. The bus and instrument subsystems will be tested and their performance characterized. Updated bus and instrument control software will be uploaded and tested.

- After sufficient experience has been gained in operating the satellite, science operations will begin. This will involve downloading telescope star field images, defining and uploading boresight set-point slew commands and designated target windows, and then downloading the resulting photometry record files.

- This will be followed by science data processing and analysis activities by the science team members, after which papers will be written and published.

- It is anticipated that bus and instrument software refinement will continue through the lifetime of the satellite, as improvements are conceived that could result in improved performance (pointing stability, signal to noise ratio, etc.).

2.3.2 System Elements Development Overview

The development of each of the four *system elements* will follow broadly similar approaches. That basic approach is summarized here per phase of the development program, with special activities noted for each element.

Phase A: Mission Definition and Planning

The basic activities that will be carried out for all four system elements (instrument, bus, ground station and GSE) are:

- Initial hardware design, in support of requirements definition for each element.

- Definition of software requirements and design approach, for the software component of each element.

Instrument-related design will be done by ISTS, and design of other system components will be done by Dynacon and UTIAS.

For the satellite bus, a decision must be made during Phase A regarding which development approach is to be followed (custom development versus technology transfer from SSTL). Some initial design work will be carried out for both options, to provide a basis for making this decision. Potential component suppliers and development costs will be estimated for the custom-design option, and a firm price for a technology transfer license from SSTL as well as financing commitments from other interested parties (e.g., CSA's Space technology branch) would be sought for the second option.

Phase B: Design

The basic activities for all four system elements during this phase are:

- Preliminary design for each element, based on requirements established in Phase A. This will include identification of potential Canadian and international suppliers for components, obtaining quotes from them, sizing of all system elements (solar arrays, batteries, reaction wheels, computer memory, etc.), and producing preliminary system configuration and layout drawings, as well as making estimates of the achievable mass, power consumption and volume for each component of the satellite. This will all be supported by detailed analyses and simulations, which will provide data for trade-offs between the main system parameters.

- Testing of the elements of the Functional Prototype Model (FPM), including prototype versions of the MOST flight software, and of the integrated FPM, in support of preliminary design decisions.

- Preparation of (minimal) design documentation to support the PDR.

- Detailed design for each element, including a make-versus-buy decision for all components, initiation of the procurement process for bought-out components, preparation of production drawings for components to be made, and development of a detailed software architecture for each computer in the system.

- Preparation of design documentation, and support of the CDR.

Again, instrument design will be done by ISTS, and design of the bus, ground control station and GSE will be done by Dynacon.

For the instrument, FPM testing will concentrate on testing prototype versions of the image processing software for tracking stars within target windows and measuring their brightness, as well as the software interfaces for commanding mode changes in that software. An output of this will be a verification of the sources of measurement error in the proposed instrument design, and approaches to assessing error magnitudes.

For the bus, FPM testing will focus on battery charge management, definition of telemetry and tele-command software interfaces, and performance of the attitude control system. A key output of this testing will be an assessment of the expected MOST pointing accuracy and stability, which will drive decisions regarding instrument CCD resolution and sensitivity, and telescope aperture and focal length.

For the ground station and GSE, FPM testing will help to define the interfaces to be built between these elements and the spacecraft, in terms of what data should be available for telemetry, and what spacecraft control modes should be incorporated into the design.

Phase C: Manufacture, Integration and Test

At the element level, work during this phase will comprise:

- Having custom components built and tested.

- Procuring and acceptance-testing commercial components.

- Assembling and integrating each element from its components.

- Conducting functional tests of each element during assembly and integration.

- Conducting verification tests of each element after assembly and integration, against each element's requirements.

The instrument will be manufactured, assembled, integrated and tested at the University of Toronto Physics Department's MOPITT lab, under ISTS supervision, making use of the clean-room and thermal-vacuum chamber there. Use of this facility will help to ensure that the optical system does not become contaminated during or after production.

The bus will be developed jointly at Dynacon and UTIAS. Bus components will be less susceptible to contamination than the instrument, and initial assembly will be carried out under normal laboratory conditions. Assembled sub-units will be transferred into a clean-room for final assembly and integration, and subsequent functional testing.

The ground station and GSE will be integrated and tested under normal laboratory conditions at Dynacon and UTIAS.

2.3.3 Work Breakdown Structure, Schedule and Cost

It is, of course, necessary at the outset of a program such as this to establish a reasonably reliable estimate of the cost of developing the spacecraft bus to be used. Unfortunately, this task is made very difficult by the fact that no organization exists in Canada with experience in building microsatellite buses. It is well known that some organizations with such experience in other countries, notably Surrey Satellite Technology Limited in the U.K., are able to provide microsatellite buses at reliable, low prices. While some companies in Canada have experience in building much larger satellites, it is well known (as demonstrated in the "Cost Modelling" analysis presented in WERTZ & LARSON) that the development approaches used by these large companies simply do not scale down to the low cost levels expected by the Small Payloads Program.

In order to estimate costs for the MOST bus, ISTS has consulted the MOST Project's industrial team member. Dynacon has prepared MOST development work breakdown structure and cost estimate, included here in Table 2.3. This includes all anticipated costs to the CSA's SPP over the development of MOST, up to the end of the first year's science operations. The plan for Phase A is more well-defined than for Phases B–E; one of the important outputs of Phase A will be a refined version of the plan that the Phase B–E section of that table is based on. The basis for this cost estimate is as follows:

- The MOST instrument design, build and test cost estimates were compiled by ISTS, based on ISTS's internal plan for instrument development.

- The launch cost is based on industry average launch costs for similar secondary payloads.

- In keeping with the assumption that the MOST system, bus and ground segment designs will be based on those for SSTL's UoSAT, the costs for bus development, ground equipment development, launch campaign, on-orbit commissioning and science operations are derived from SSTL's UoSAT costs. The manner in which these were derived is summarized next.

Several sources were consulted to establish cost breakdowns for systems based on SSTL's microsats. The primary ones were:

Table 2.3

MOST Estimated Budget for Primary Bus Development (Development of New Bus Design)	Total Cost	Cost Offsets	Net Cost to CSA/SPP
Phase A: Mission Planning and Definition	*788,740*	*331,000*	*457,740*
A1: System Requirements Generation & Review (SRR) Meeting	18,498	5,000	13,498
A2: Mission Analysis	70,203	40,000	30,203
A3: Science Requirements Definition	14,500	10,000	4,500
A4: System Initial Design	80,036	30,000	50,036
A5: Instrument Initial Design	27,215	12,000	15,215
A6: Bus Initial Design	145,000	80,000	65,000
A7: Ground Equipment Initial Design	61,617	44,000	17,617
A8: Develop Functional Prototype Model	200,238	110,000	90,238
A9: Phase B-E Planning	48,488	0	48,488
A10: Phase A Final Review Meeting	14,865	0	14,865
A11: Project Management	76,936	0	76,936
A12: Reportage	31,145	0	31,145
Phase B-E: Design Through Flight	*6,649,769*	*3,122,500*	*3,527,269*
Phase B: Design	799,100	235,000	564,100
B1: System Preliminary Design	56,125	23,000	33,125
B2: Instrument Preliminary Design	31,950	0	31,950
B3: Bus Preliminary Design	66,690	23,000	43,690
B4: Ground Equipment Preliminary Design	33,000	23,000	10,000
B5: FPM Testing	50,300	18,000	32,300
B6: Preliminary Design Review (PDR) Meeting	39,063	10,000	29,063
B7: System Detailed Design	79,150	23,000	56,150
B8: Instrument Detailed Design	41,520	0	41,520
B9: Bus Detailed Design	292,460	90,000	202,460
B10: Ground Equipment Detailed Design	64,780	10,000	54,780
B11: Critical Design Review (CDR) Meeting	44,063	15,000	29,063
Phase C: Manufacture, Integration and Test	3,371,903	1,156,000	2,215,903
C1: Build and Test Bus	2,172,000	497,000	1,675,000
C2: Build and Test Instrument	43,440	0	43,440
C3: Build and Test Ground Support Equipment	159,690	66,000	93,690
C4: Microsat Integration and Functional Testing	185,450	92,000	93,450
C5: Microsat Qualification & Acceptance Testing	122,960	40,000	82,960
C6: Microsat Environmental Testing	300,175	250,000	50,175
C7: Ground Station Build and Test	326,000	186,000	140,000
C8: Mission Readiness Review (MRR) Meeting	29,063	0	29,063
C9: Initiate Public Outreach Contest	33,125	25,000	8,125
Phase D: Launch Support	1,364,808	1,216,500	148,308
D1: Complete Launcher Data Requirements	203,645	150,000	53,645
D2: Flight Readiness (FRR) Meeting	29,063		29,063
D3: Transport Microsat and GSE To Launch Site	12,500	4,000	8,500
D4: Integrate and Checkout Microsat at Launch Site	41,150	20,000	21,150
D5: Support Microsat Integration With Launcher	47,300	25,000	22,300
D6: Participate in Launch Preparation Exercises	31,150	17,500	13,650
D7: Launch	1,000,000	1,000,000	0
Phase E: Flight Operations	587,675	490,000	97,675
E1: Microsat Commissioning	86,150	60,000	26,150
E2: On-Going Engineering Support (1 year)	60,763		60,763
E3: Mission Primary Science Operations (1 year)	110,763	100,000	10,763
E4: Science Data Analysis	175,000	175,000	0
E5: Publication of Science Results	130,000	130,000	0
E6: Select Public Outreach Contest Winner(s)	25,000	25,000	0
E7: (Public Outreach and Secondary Science Ops.)	0	0	0
On-Going Activities Through Phases B-E:	526,284	25,000	501,284
BE1: Project Management	354,160	25,000	329,160
BE2: Reportage	31,849	0	31,849
BE3: Meetings	32,150	0	32,150
BE4: Travel and Living	76,875	0	76,875
BE5: Transportation	31,250	0	31,250
Program Total	*7,438,509*	*3,453,500*	*3,985,009*

Table 2.4

MOST Estimated Budget for Secondary Bus Development (Technology Transfer of Existing Bus Design)	Total Cost	Cost Offsets	Net Cost to CSA/SPP
Phase A: Mission Planning and Definition	788,740	331,000	457,740
Phases B–E: Design Through Flight	9,195,000	6,631,500	2,563,500
Phase B: Design	3,175,000	2,700,000	475,000
Phase C: Manufacture, Integration and Test	4,155,000	2,000,000	2,155,000
Phase D: Launch Support	630,000	1,416,500	(786,500)
Phase E: Flight Operations	660,000	490,000	170,000
On-Going Activities Through Phases B–E:	575,000	25,000	550,000
Program Total	9,983,740	6,962,500	3,021,240

Task Name	Start Date	End Date
Phase A: Mission Planning & Definition	02-06-97	23-12-97
Phase A Review	31-12-97	31-12-97
Phase B: Design	01-01-98	31-12-98
PDR	31-03-98	31-03-98
CDR	31-08-98	31-08-98
Phase C: Manufacture, Integration & Test	02-06-98	03-01-00
Instrument/Bus Integration	31-12-99	31-12-99
Phase D: Launch Support	04-01-00	02-10-00
Launch	30-09-00	30-09-00
Phase E: Flight Operations	03-10-00	28-09-01
End of Primary Mission	30-09-01	30-09-01
(Start of Secondary Science Mission)	01-10-01	...

Figure 2.6: MOST Development Schedule

- A detailed quote provided by SSTL to Dynacon, listing the cost of providing various elements of an SSTL microsat bus technology transfer program to Canada. This quote was prepared with the assumption that the "standard" SSTL microsat bus would be used with little modification, which matches the MOST initial design ground-rules.

- The "PoSAT-1" chapter of WERTZ & LARSON, which provides details of the mass, power and cost breakdowns of the various components of the PoSAT-1 microsat and its ground element, that SSTL built for Portugal in 1992/93.

These estimates were then adjusted to reflect the addition of high-performance attitude control capability to the standard SSTL bus, a capability which Dynacon is currently working with SSTL to develop. It was assumed that once a MOST bus design is established, then Dynacon and UTIAS could *build and test* that bus at a dollar cost similar to the cost that SSTL would charge; this assumption is based on the extensive in-kind contributions that MOST will have access to, as a result of UTIAS staff and students participating in the development process. SSTL cost quotes were also used as the basis for estimating the amount of effort required to support the launch of the MOST microsat, commission it once on orbit, and operate it thereafter. In numerous places the SSTL costs weer "grossed up," to account for the greater efficiency that SSTL enjoys as a result of their years of experience.

As for *establishing a bus design,* the two options discussed above were costed separately:

- The baseline bus development approach, which forms the basis for this proposal, is costed in Table 2.3. This approach assumes that Dynacon and UTIAS will develop a new bus design, based on information available about the design approach of SSTL's microsat and ground segment equipment. Dynacon's experience in designing similar systems (such as the DICE microsat experiment) was used to estimate the MOST bus design costs there. This approach is fully compliant with the cost, technical and programmatic guidelines set out in the SPP AO. Figure 2.6 is a Gantt chart illustrating the schedule by which this work will be carried out; this schedule is slightly longer than the 2-year schedule suggested in the SPP AO, in order to accommodate the academic schedules of the university students who will take part in the development; it is consistent with a launch in late 2000 on the Radarsat 2 launch vehicle.

- The secondary design approach is based on establishing a technology transfer program between SSTL and Canadian organizations, in parallel with the MOST system development, which would result in a Canadian team being trained in building SSTL-style microsat buses, and the CSA licensed to build future microsats based on that design. A (less-detailed) cost estimate for this approach is presented in Table 2.4. If suitable co-financing can be arranged (from other interested CSA branches, for example) to cover the initial technology transfer investment, the result would be a lower cost to the SPP for the MOST mission, as well as an increase in the certainty that the MOST bus would work

reliably (based on the long, successful flight history of the SSTL bus, with 12 fully successful missions to date), and the establishment of a capability to build future SPP (and other) microsats in Canada at similarly low per-flight cost.

Both cost estimate tables show three columns of figures. The right-hand column is the net cost to be covered by contracts issued by the CSA's SPP for MOST; it represents the difference between the "Total" costs per task, and various "Cost Offsets." These offsets include cash and in-kind contributions from a variety of non-SPP-contract sources:

- The largest single cost offset is $1M for the MOST launch, which is assumed to be donated by NASA.

- The MOST mission will depend critically on Dynacon's HPAC attitude control subsystem enhancements. The development of this has been supported for several years by the CSA's Space Technology branch. Initial work was done under the DICE project, while performance analysis for the MOST mission was initiated under the SACTS study reported in CARROLL, including simulator development and assessment of cost versus performance based on different approaches to ACS equipment selection. Development and flight test of a space qualified miniature reaction wheel is underway, under a CSA/STB contract, for which SSTL is donating a flight-test. Preliminary design of the HPAC subsystem for the SSTL microsat bus is being funded by another CSA/STB contract. The total value of the portions of these contracts that technically benefit MOST is about $700K. In addition, cash and in-kind contributions from SSTL, NSERC and ISTS could bring the total external contributions in support of MOST's HPAC subsystem to as much as $1M.

- UTIAS is the next largest in-kind contributor to MOST. By employing UTIAS engineering students directly in MOST design, building and testing (similar to the way that UTIAS students participate in DICE development), a great amount of skilled engineering labor will be accomplished at little or no cost; the benefit of this to the MOST project will be in excess of $400K, based on six students at a time working part-time for 18-months on MOST. In addition, UTIAS is contributing access at no charge to a clean-room for MOST assembly and an attitude-control testbed facility, and it is expected that UTIAS will charge a reduced overhead rate (15%, rather than the PWC-approved 65%) for all MOST-related expenses. The total benefit to MOST from these contributions approaching $700K. This does not even include the (quite likely) potential for UTIAS to attract NSERC funding to match some of the UTIAS MOST funding, so this figure is likely to increase substantially.

- Similarly, both ISTS and the University of Toronto MOPITT lab will be charging to the MOST contract using overhead rates lower than those charged to "outside" organizations, which has lowered the MOST instrument development cost by $100K or more. ISTS is also expected to contribute $50K to the development of the UTIAS attitude control testbed that will be used to test the MOST Functional Prototype Model in Phase A.

- The MOST Science Team will carry out many MOST-related activities under NSERC and university funding, including data analysis and publication of results. The value of this contribution is at least $200K.

- The Royal Astronomical Society of Canada will be contributing by running the MOST Observer's Contest using their own financial resources.

- CSA personnel are expected to take part in the MOST project. It is anticipated that SPP personnel will take the lead in arranging for the MOST launch opportunity, including much of the launcher interface documentation preparation. Space Operations branch personnel are expected to use the David Florida Laboratory facilities to carry out most of the environmental tests for MOST, to lead the MOST launch campaign, and to commission and operate MOST after launch. Space technology branch personnel have expressed interest in participating in development of the MOST bus; an equivalent 2 PYs of effort by STB personnel to help design, build and test MOST has been assumed.

- Finally, the possibility of co-funding from other CSA branches, to invest in transferring SSTL microsat technology to Canada, has been raised by Dynacon. There appears to be significant interest in this concept at this point, and this could represent an avenue of significant cost savings to the SPP for MOST, as well as for other future SPP microsats.

2.3.4 Management Plan

This management plan specifies the roles of the Investigator Organization, industry, students and the government, as requested in the SPP Implementation Plan. While space does not permit providing much of the other information that could be included in a complete management plan (specifying project control approach, subcontracting procedures, etc.), it should be noted that the principal developers of MOST (the Instrument Services Lab at ISTS, and Dynacon Enterprises Limited) are both very experienced at running successful engineering development projects, and senior managers from both will apply their best management practices during MOST development.

All technical decisions that affect the performance of MOST as an astronomical telescope will be made by the Principal Investigator, Dr. Slavek Rucinski. This includes issues of instrument design, and services (e.g., attitude control performance) supplied to the instrument by the bus. Dr. Rucinski will represent both ISTS and the University of Toronto Astronomy Department for the MOST project.

The management of the development of the MOST instrument will be carried out by John Connor, a senior project manager at ISTS. His development team will participate in deciding on the requirements and specifications for the instrument, and subsequently will develop preliminary and detailed designs for it. They will then monitor the U. Of T. MOPITT lab as the instrument is built and tested. ISTS will operate under a series of contracts from the CSA's Space Science Branch. ISTS will also develop the software for on-board processing of the instrument's science CCD detector. They will employ students (from York University, and the University of Toronto Astronomy Department) during various of these activities.

The MOPITT lab at the University of Toronto, managed by Professor Jim Drummond, will construct and test the MOST instrument, under subcontract from ISTS. This group will also participate in the development of the instrument specifications, and will participate in reviewing its design. This group may also host the integration of the bus and instrument in their clean-room, and carry out integrated satellite thermal testing; in this case, they will work closely with Dynacon and ISTS in doing so.

Dynacon Enterprises Limited will lead the MOST bus and ground segment development; the Dynacon Project Manager for MOST will by Dr. Kieran Carroll, Dynacon's Manager, Space Projects. During Phase A this will be under a subcontract from ISTS; after that, it will be under one or more contracts from the CSA's SSB. Dynacon will be responsible for the overall engineering management of the MOST bus and ground segment equipment development, as well as the MOST system-level design and mission analysis. A team of Dynacon engineers will work closely with students and staff at UTIAS, as well as engineers from the CSA's Space Technology and Space Operations branches to set requirements for this equipment, design it, build it, integrate it and test it.

UTIAS will work closely with Dynacon during the bus development process, under one or more subcontracts from Dynacon. The work there will be led by Professor Peter Hughes (UTIAS Space Systems Engineering professor). Under his supervision, staff from UTIAS will organize students to participate in the MOST design via a graduate-level spacecraft design course, other course projects, and graduate theses. Some of these staff and students will go on to participate in MOST bus building, integration and testing, which will

be carried out in a clean-room facility at UTIAS. UTIAS will also contribute facilities to test MOST attitude control system components.

The CSA will, of course, be an integral member of the MOST team. The Space Science Branch staff will participate in setting up and monitoring the ISTS and Dynacon contracts, as well as reviewing design work, arranging for the MOST launch opportunity, and managing the MOST/launcher interface. CSA Space Operations staff are assumed to participate in MOST integration and testing prior to launch, and to be responsible for MOST satellite operations after launch. CSA Space Technology staff will participate in reviewing mission, system and bus designs, and have expressed an interest in participating in design and testing work.

2.3.5 Facilities Required

Several facilities will be required to support the development of the MOST equipment. The facilities likely to be used are:

- *The University of Toronto Physics Department's MOPITT lab.* This includes a clean-room and thermal-vacuum test chamber, as well as access to the Physics Depertment's extensive fabrication and electronics workshops. This will be used for building the MOST telescope instrument, as well as carrying out functional tests of it, and thermal-vacuum tests to verify passive thermal radiator performance. This could also be used for some integrated functional and thermal-vacuum testing of the entire MOST microsat.

- *UTIAS.* This will include a clean-room, in which the MOST bus will be assembled, and in which bus functional tests will be carried out. MOST will have access to the UTIAS machine shop and electronics technicians. The MOST Functional Prototype Model will be located at UTIAS, making use of a planned UTIAS 3-axis attitude control system testing facility.

- *ISTS Instrument Services Lab.* This may be used to carry out some optical and calibration testing of the MOST instrument and detectors.

- *The CSA's David Florida Laboratory (DFL).* This could be used for integration of the MOST microsat, and integrated functional testing. Depending on availability of equipment at DFL, testing there could include • Solar array and power subsystem functional testing, using a sun-source simulator • Launch loads, separation shock and vibration testing, including a modal survey • EMC testing • Antenna radiation pattern testing • Microsat inertia property testing • Thermal vacuum testing • Magnetic grooming.

- *The CSA's ODIN ACS Testbed.* This includes a two-axis rate table and star simulator, which could be used for testing of components of the MOST attitude control system, most likely after microsat integration.

In addition, several new facilities will be developed to support MOST:

- A ground control station. While the planned ground station design is small enough to be installed virtually anywhere with a clear sky view, the baseline approach is to install this at the CSA's St. Hubert headquarters, and to operate it using CSA Space Operations Branch personnel. Alternately, it could be located at ISTS, UTIAS, or the David Dunlap Observatory, which could reduce operating costs. The data gathered here will be made available to the science team via the Internet.

- A data archiving facility. This will comprise a computer workstation with Internet access, and with some suitable data viewing software capabilities. It should be conveniently accessible to the MOST Principal Investigator, and so will be either at ISTS or the University of Toronto Astronomy Department.

Each MOST science team member will conduct his or her own analyses using their own university computing facilities.

2.3.6 Risk Analysis

All space systems are subject to a variety of risks, due to the impossibility of accessing an orbiting spacecraft to reset or repair any failed equipment, and MOST is no exception. These risks are controlled by identifying them early in the design cycle, and designing into the system features to make it robust against failures. An initial analysis of the risks to MOST is presented here. During Phase A this analysis will be extended to include an initial failure modes and effects analysis, to provide designers with a basis for designing robustly.

One of the greatest risk faced by any microsatellite is *launcher related.* According to a database of more than 100 past small satellite missions, maintained by AeroAstro Corporation (as cited by FLEETER), the probability that a launch vehicle will fail to place a small satellite into its correct orbit is greater than 25%. This includes the effects of launcher failures (e.g., explosions), as well as cases where *an* orbit is reached (but not the planned orbit), and cases where the satellite fails to separate from its launch vehicle. The primary way to control this is to choose to launch on a vehicle with demonstrated high reliability (such as the Delta 2 that Radarsat 2 will launch on).

Once a correct orbit has been achieved and MOST has been released successfully from the launch vehicle, there are a variety of risks that it will face. Some of these are *instrument-related*, such as the risk that:

- A CCD detector chip, or one of the CCD electronics processing board, or the wiring associated with these could fail, causing failure to collect science data. The MOST design controls these by incorporating dual detectors and processing boards.

- The temperature of the detector mounting cold-plate drifts enough to introduce a serious error signal into the science data, due to variation of pixel scale factor with temperature. MOST could control this in several ways, for example with redundant, controllable heaters on the cold-plate to maintain temperature within a narrow region, or through on-board signal calibration based on cold-plate temperature sensor measurements.

Other errors are *satellite-control related*, such as the risk that:

- The command receiver radio, telecommand unit, control computer or some other critical component in the command link might fail. This is controlled by a combination of redundant design, use of proven designs for critical components, and extensive ground testing.

- An erroneous attitude control command might be issued (by ground control error, or by single-event upset of computer logic in the on-board computers), causing MOST to enter an attitude mode that causes solar power collection to drop (e.g., tumbling). If power levels drop fast enough, the batteries might be depleted before corrective commands can be issued from the ground. This is controlled using measures such as on-board error detection, watch-dog timers for the on-board computers, designing-in a "safe-hold" attitude control mode that will maintain positive power margin (e.g., face one solar panel towards the sun), etc.

- An attitude control system component (reaction wheel, magnetorquer, rate sensor, sun sensor) might fail, causing loss of attitude control. This is addressed by means such as designing-in redundant components (e.g., a "skew" reaction wheel backing-up the X, Y and Z-axis wheels), designing to be able to switch one component for another (e.g., magnetometers to replace data from a failed sun sensor), and suitable safe-hold modes.

- That the attitude control system might not achieve sufficiently performance; insufficient accuracy would result in the target star wandering out of the telescope field of view (resulting in data record interruption), while insufficient pointing stability could result in the target star wandering out of its target window during a single sample period (causing an erroneous negative star brightness signal bias). This will be controlled by extensive analysis and testing of the ACS on the ground, as well as carrying out on-orbit experiments beforehand (such as the reaction wheel test-flight planned by Dynacon on an SSTL microsat) to validate the basis for these analyses.

There are also the *programmatic risks* that development difficulties might cause schedules to slip or budgets to rise. These will be controlled by including milestone reviews into the development process to expose any such problems as early as possible, and by employing Early Prototyping in Phase A (building the Functional Prototype Model) to gain familiarity with the behavior of equipment that is functionally similar to MOST.

2.4 MOST Benefits to Canada

The MOST team firmly believes that the Canadian space program can be a powerful driver for the development of technological expertise and capabilities, a catalyst for the development of new Canadian space-related products for both home and export markets, and a profound symbol reflecting Canadian values to the Canadian public by means of great accomplishments. The MOST mission has been designed with these goals in mind, in addition to the specialized goals of stellar photometry. In this section, the main benefits to Canada that will accrue from MOST are summarized.

2.4.1 Space Science Instrument-Building Infrastructure

Both the ISTS Instrument Services Lab, and the MOPITT lab at the University of Toronto, have been developing valuable expertise in the design, manufacture and testing of state-of-the-art space science instruments for the CSA's Space Science program. These two groups will work closely together to develop the MOST instrument. By keeping these groups employed, the MOST project will be supporting the infrastructure investments that the CSA has made in their facilities (e.g., for the MOPITT and WINDII instruments), which will be applicable to other small, optical CCD-based instruments.

In addition, MOST will give these groups experience in space astronomy instrument development which may lead to new opportunities for Canadian participation in international space science missions. It is quite conceivable that the MOST mission results will create interest in other countries to develop a similar low-cost space telescope; after all, with its long dwell times on each target, MOST will only be able to take measurements from a small fraction of the set of

potential target stars, leaving many others that could be targeted in a follow-on mission. Canada would be in an ideal position to supply the instrument (in addition to attitude control hardware) for any such future mission.

2.4.2 Microsat Bus-Building Infrastructure

Several other countries, including the United States and England, have developed smallsat and microsat programs that have revitalized their space programs, and represent one of the main sectors of the space market to experience growth in recent years. This is typified by a synergistic relationship between technology development to miniaturize spacecraft components, and dramatic reductions in spacecraft life-cycle costs. A key factor fueling this cycle has been the deep involvement of some universities in development of small, inexpensive demonstration satellites (such as the University of Surrey in England, and schools such as the University of Colorado, Weber State University and Stanford University in the United States).

The goals of the CSA's Space Science smallsat and small payloads programs recognize the importance of these new space markets, and the important role that a national space program can play in financing the development of these national capabilities. Dynacon and UTIAS believe that a program of Canadian microsats, for space science and space technology demonstration missions, is the key that will open the door of this market to Canadian companies. The most successful international model for this type of enterprise is the university/industry teaming of the University of Surrey with SSTL. Dynacon and UTIAS intend nothing less than to develop a similarly successful series of Canadian microsatellites, using a standard, low-cost modular bus design, based on UTIAS's unequalled (in Canada) space systems engineering training and research expertise, and Dynacon's ability to manage space systems development projects. The first microsat in that series is the DICE Space Shuttle experiment, and MOST could become the second; Dynacon is discussing the possibility of a CSA space technology microsat being the third.

There would be an immediate benefit to the CSA from the development of this infrastructure. CSA Space Science instruments would achieve the frequent, low-cost access to space envisaged in the SPP objectives, with the result that Canadian space scientists could achieve more science results at a lower cost, and with greater control over mission objectives. CSA space technology development projects could confidently aim to develop and test flight hardware, knowing that money would not have to be spent offshore in order to test-fly the technologies that they develop.

2.4.3 Promotion of Canadian Space Technology Product Exports

Canadian industrial developers would also reap benefits from a made-in-Canada microsat program. The current necessity to purchase expensive payload space on foreign spacecraft in order to flight-qualify prototype equipment, is currently placing a financial strain on the development programs of several potential future Canadian spacecraft products. This program would not only focus Canadian industrial effort on the development of components for the expanding small spacecraft market, it would provide a low-cost approach via which Canadians could achieve the all-important milestone of flight testing.

The first example of this effect would be important benefits for Dynacon's miniature reaction wheel product. A "spin-off" technology from the CSA-funded DICE project, Dynacon is developing this as a commercial product for export into the growing international microsat market, with CSA export-development assistance. An experimental flight test of a single wheel is planned for 1997 on an SSTL microsat mission, which will give the product some market exposure. The MOST mission could be the first *operational* use of this product in a 3-axis attitude control application. Success here will significantly increase its export marketability. This relates to the "home market" effect—potential export customers will tend to view demonstrations of CSA support for a Canadian product as an indication of the product's quality; since the CSA is in a better position than them to examine and judge the product's development. In the eyes of the international microsat market, the adoption of the MOST mission by the CSA's SPP would be an unmistakable vote of confidence in Dynacon's HPAC product.

Last but not least, Dynacon's initial market channel for the HPAC product is SSTL. If the CSA chooses the option of developing a Canadian microsat bus capability via technology transfer from SSTL, this will tend to cement SSTL's reliance on Dynacon as a supplier of advanced attitude control capabilities for SSTL missions. Investment by the MOST mission in the non-recurring engineering for a MOST HPAC subsystem, if it is 100% compatible with SSTL's microsat bus design, would drop Dynacon's recurring costs for these subsystems to a level low enough that SSTL would find it financially far more attractive to buy HPAC subsystems from Dynacon than to develop a new design of their own. In their accompanying support letter, Dynacon has proposed an intriguing "no exchange of funds" method for acquiring some of the SSTL technology that could formally commit SSTL to buying a large number of Canadian-built HPAC subsystems.

2.4.4 Space Science Public Outreach Activities

The MOST public outreach activities that are outlined in Section 2.1.7 have an enormous potential to increase the consciousness of the Canadian public about the activities of the CSA's Space Science program, by using a MOST Observer's Contest to generate public excitement in the MOST mission. The plan to involve high-school students in this contest is intended to capitalize on the excitement shown by school children of all ages in space activities, and to encourage students to transfer that interest to their math and science studies. Students competing for MOST observation time will have to learn about advanced topics such as data filtering, Fourier transforms and oscillating systems in order to plan their proposals. With CSA and RASC help, the MOST team can make educational material available to contestants that will be within the grasp of bright high-school students, to enrich and help motivate their pre-university studies. Canada will benefit from the resulting increase in student interest and ability, as well as by the positive national self-image that will come from increased awareness of Canada's space program activities.

2.5 References

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