

CHIPS Microsatellite Optical System: Lessons Learned

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ABSTRACT

The Cosmic Hot Interstellar Plasma Spectrometer (CHIPS) observatory launched on 12 January 2003, and was the first and only successful GSFC UNEX (NASA Goddard Spaceflight Center University Explorer class) mission. The UNEX program was conceived by the National Aeronautics and Space Administration (NASA) as a new class of Explorer mission charged with demonstrating that significant science and/or technology experiments can be performed by small satellites with constrained budgets and a limited schedule. The purpose of the observatory was to examine details of the local bubble thermal pressure, spatial distribution and ionization history. The observatory was also used to observe solar spectra, both scattered from the Lunar surface and via a fortuitous 2nd order scattering path. CHIPS confirmed that spectral features within the 90-260Å band were much dimmer than was predicted by contemporary theories, and operated four years beyond its design lifetime. The observatory was placed in an extended safe-hold mode in April of 2008 for budgetary purposes. The spectrometer consisted of six spectrograph channels which delivered $>\lambda/100$ resolution spectra to a single detector. Cost constraints of UNEX led to a design based on a traditional aluminum structure, and an instrument with a large field of view (5° x 26°). All optical and optomechanical systems on the spectrometer performed flawlessly on orbit. We discuss the challenges, difficulties and lessons learned during the design, fabrication and execution stages of the mission.

Keywords: Shape Memory Alloy, Semi-Kinematic, Flexure, Zerodur, UNEX, CHIPS, Local Bubble
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1. INTRODUCTION: CHIPS MISSION



Figure 1: CHIPS launched with ICESAT on 12 January 2003 from Vandenberg Air Force Base on a Delta-II launch vehicle into a 650km, 98° inclination orbit.

The University-Class Explorer Program, or UNEX, was conceived in the mid-1990s as a means to expand dramatically the number of orbiting science payloads. Previous NASA missions lasted many years, and cost

hundreds of millions of dollars to execute. Since the 1950s, the suborbital sounding rocket payloads launched by NASA produced significant scientific advancements, and trained several generations of leaders in numerous areas of Space Science. UNEX was designed to move the low-cost, higher risk and yield sounding rocket approach to orbital missions. In this, it was to bridge the gap between sounding rocket science and the Small Explorer (SMEX) class of missions managed by the Goddard Spaceflight Center (GSFC). By allowing the NASA Centers to focus on larger-scale missions, while using the talents of university-led research groups to focus on smaller, riskier missions with high potential for focused scientific yield, a new army of scientists and engineers could be trained as future technological leaders.

CHIPS was the first and only UNEX mission selected and developed for flight¹. It launched from Vandenberg Air Force Base (VAFB) on a Delta-II 7320-10 launch vehicle as a secondary payload in an Astrium reduced height dual payload attach fitting (RHDPAF). The primary payload was ICESAT, which carried the Geosciences Laser Altimeter System (GLAS). CHIPS was a 64kg observatory carrying a single experiment, an extreme ultraviolet (EUV) spectrograph designed to study the faint glow of the local bubble, a million-degree plasma theorized to surround the solar system and neighboring stars. CHIPS data provided information on the electron temperature, ionization conditions and the cooling mechanisms of the hot plasma comprising the interstellar medium. The spectrometer operated at wavelengths between 9 and 26nm, with a field of view (FOV) of 5° by 25°. The baseline mission was one year, however the observatory functioned nominally for five years before being placed in hibernation in 2008. CHIPS initial science results were presented at the AAS High Energy Astrophysics Division meeting in 2003. Mission results may be found in Hurwitz².

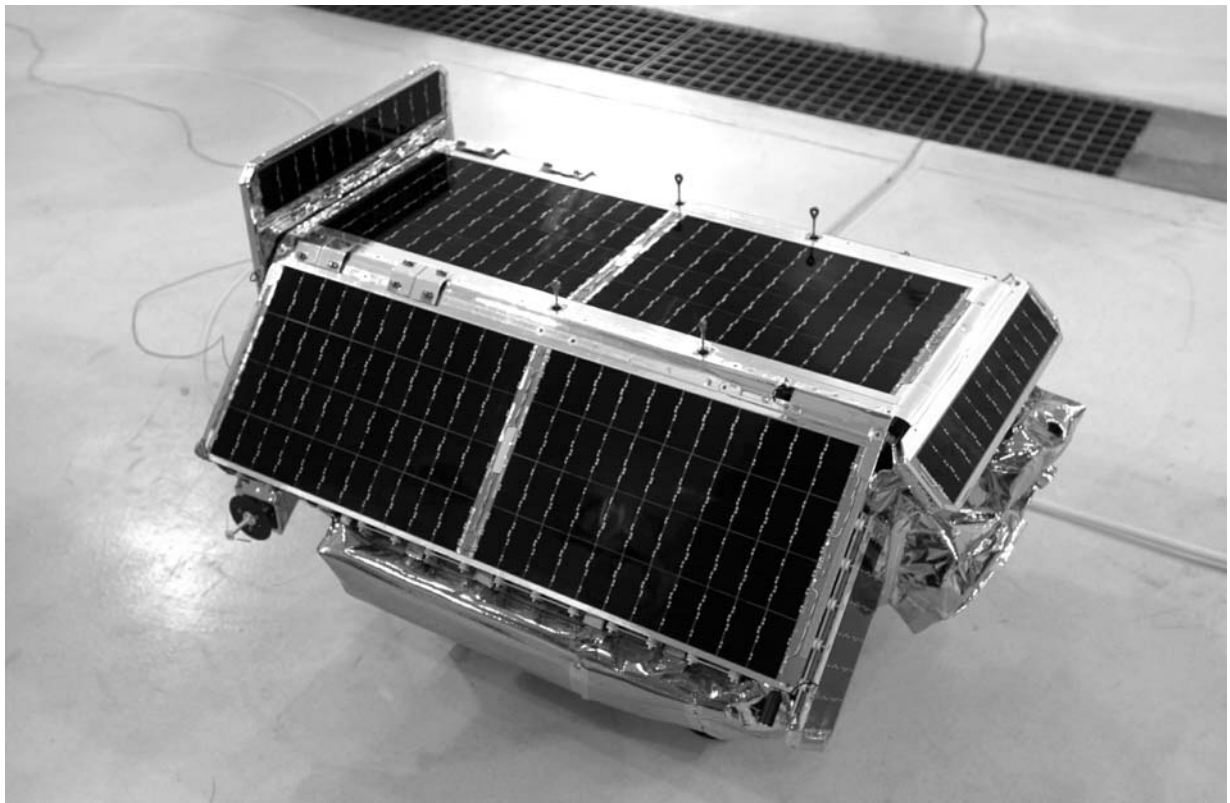


Figure 2: CHIPS Microsatellite was a 64kg 3-axis stabilized observatory with dual-junction GaAs solar arrays, an S-band transponder and an extreme ultraviolet spectrometer.

The CHIPS observatory^{3,4} included a 3-axis stabilized spacecraft and integrated avionics package provided by SpaceDev, and was based on experience from a number of AMSAT microsattellites. The attitude control system, provided by Dynacon, consisted of four momentum wheels, three magnetic torque rods, one medium and six coarse sun sensors, a magnetometer, rate sensors and a lunar sensor. The 3-axis stabilized configuration allowed for a full-sky survey as well as deep, pointed observations of interesting regions. Dual-junction GaAs/InP/Ge solar cells installed on body-mounted aluminum honeycomb panels, along with fiber nickel cadmium batteries, provided power for the observatory. Small keep-alive solar panels were installed opposite to the main solar array, and allowed the observatory to remain power-positive in safe-hold mode in any orientation relative to the sun. The optical system and lunar sensor were designed to allow passage of the sun through their fields of view without damage. The low Earth orbit (LEO) of CHIPS passed through the polar electron belts as well as the South Atlantic Anomaly (SAA). The avionics package was made largely of commercial-grade parts, and all electronics could be power-cycled via ground station commands via a command decoder to clear any radiation-induced latchups. As a lesson learned from the ill-fated Soviet Phobos 1 Mars mission, the receiver could not be shut off by ground command. In the event no command was received for seven days, the entire avionics package (including the receiver) would be power cycled automatically to clear any single-event non-destructive latchups.

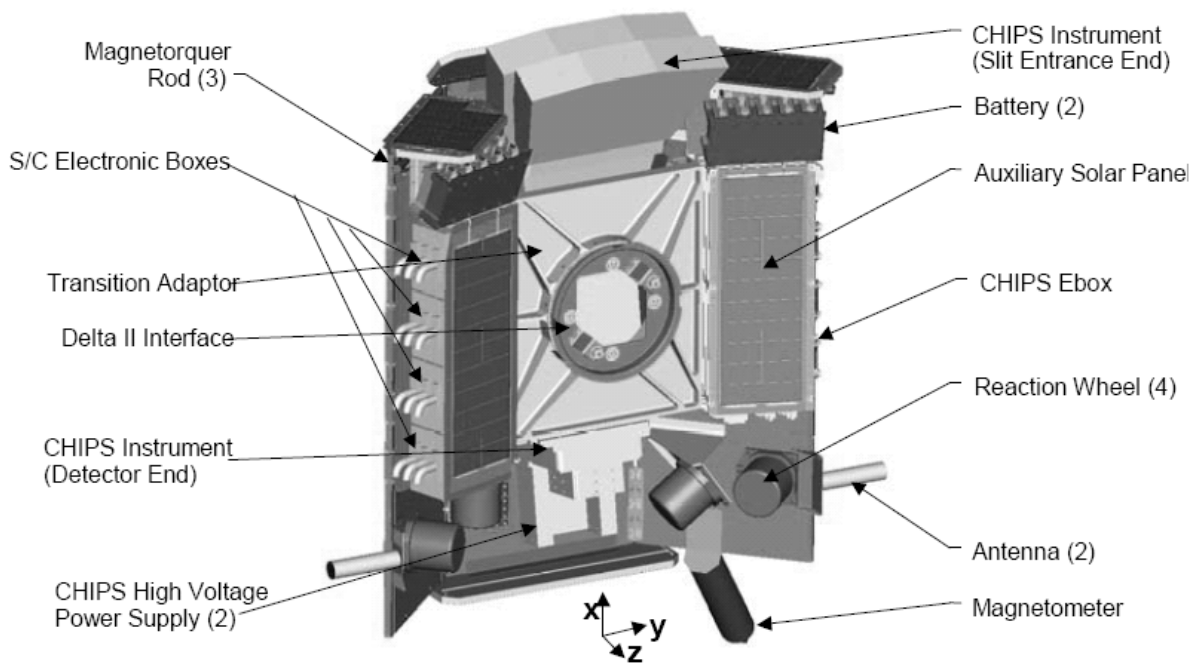


Figure 3: Baseline CHIPS observatory

2. OPTICAL SYSTEM

CHIPS Mission science requirements called for a spectrometer with a spectral resolving power of $\lambda/\Delta\lambda \geq 100$. An additional mode in which the 250 μm nominal slits could be widened to 1000 μm was also required. Details of the optomechanical design of CHIPS can be found in^{5,6}. Spectrometer mass, volume and power budgets were driven by available launch vehicle resources (SPE2 Delta-II Secondary Payload) at the time the baseline design was frozen for fabrication, as well as the integration constraints with the 3-axis stabilized microsattellite bus. The optical system initially had nine channels feeding light to a single detector. Volume, mass and launch vehicle separation system clampband moment restrictions necessitated a mid-program descoped from nine to six channels. The spectrometer was designed to fit in the <15cm gap between the

spacecraft transition adapter and solar array. Two independent layers of multi-layer insulation (MLI) were installed on the spectrometer to prevent image wander induced by variable temperature differentials between hot solar arrays and the cold transition adapter.

Available power for the spectrometer (<20W) was limited by the area of solar arrays which could be fit into the secondary payload volume, and left over from the power budget required by the spacecraft for attitude control, communication, telemetry and data processing.

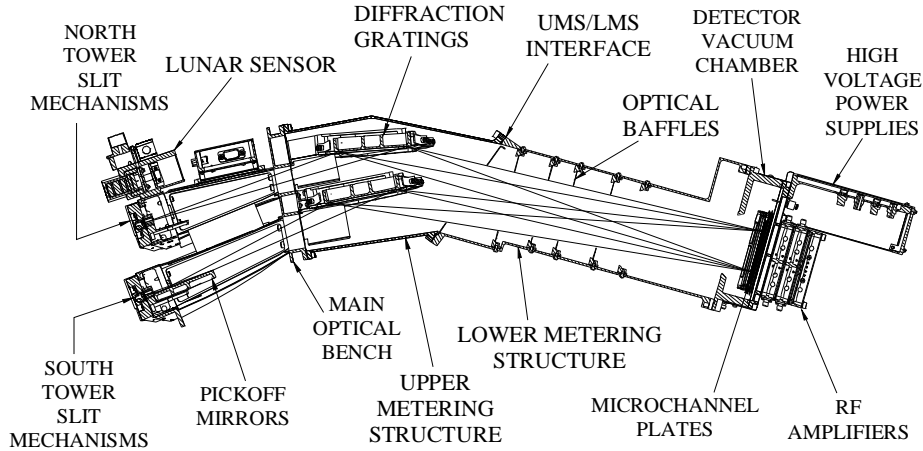


Figure 4: CHIPS Baseline design. Six optical channels delivered light to a single MCP detector. The spectrometer and microsatellite were designed to fit in the 30cm gap between the Delta-II avionics section and outer skin.

The CHIPS spectrometer (Figure 1) consisted of six identical channels delivering diffuse spectra to a single focal plane. The detector focal surface was a NaBr photocathode microchannel plate (MCP), with a crossed delay line readout system. Diffuse EUV radiation entered each spectrograph channel via a 7cm x 250µm photoetched BeCu slit. Incoming light intercepted a weight-relieved Zerodur grating, and the first internal order was directed toward the focal plane. (See Figure 5 for a description of the central channel.)

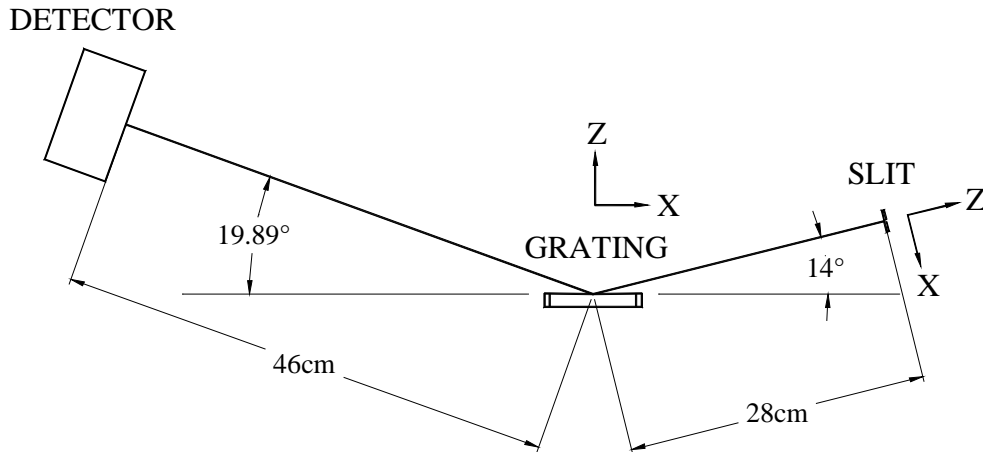


Figure 5: Central channel description. Light enters the optical system through a 250µm slit, intercepts a cylindrical varied line spacing grating, and internal orders are directed to an MCP detector.

A cylindrical (147.8cm radius), varied line spacing¹, rhodium coated diffraction grating (replicated from a mechanically ruled submaster) both dispersed incoming radiation and re-imaged the entrance slit on the flat detector focal surface. Peak geometric performance was at the center of the band, with increasing aberrations at the extremes of the bandpass. The diffraction grating blanks have two axes of symmetry, while the ruling pattern has only one. To prevent incorrect installation of the gratings, an asymmetric hole pattern was employed on the blanks. One important lesson learned was that a knowledgeable quality assurance inspector should be present, and equipped with a coherent light source and clearly labeled drawings at the beginning of the replication process to verify proper orientation of the varied line spacing profile on the grating blanks.

One of the many novel features of the CHIPS optical configuration was lack of a cross-dispersion imaging requirement. This allowed a six-fold (initially nine-fold) increase in sensitivity by coaligning the spectrograph channel outputs on a single detector (see Figure 6). Pickoff mirrors were included on the three aft channels to coalign their FOV with the front channels. Direct sneak paths to the gratings were discovered during testing of the pickoff mirror channels, and aluminum baffles were installed within the slit wheel and below the slit housing to block these paths.

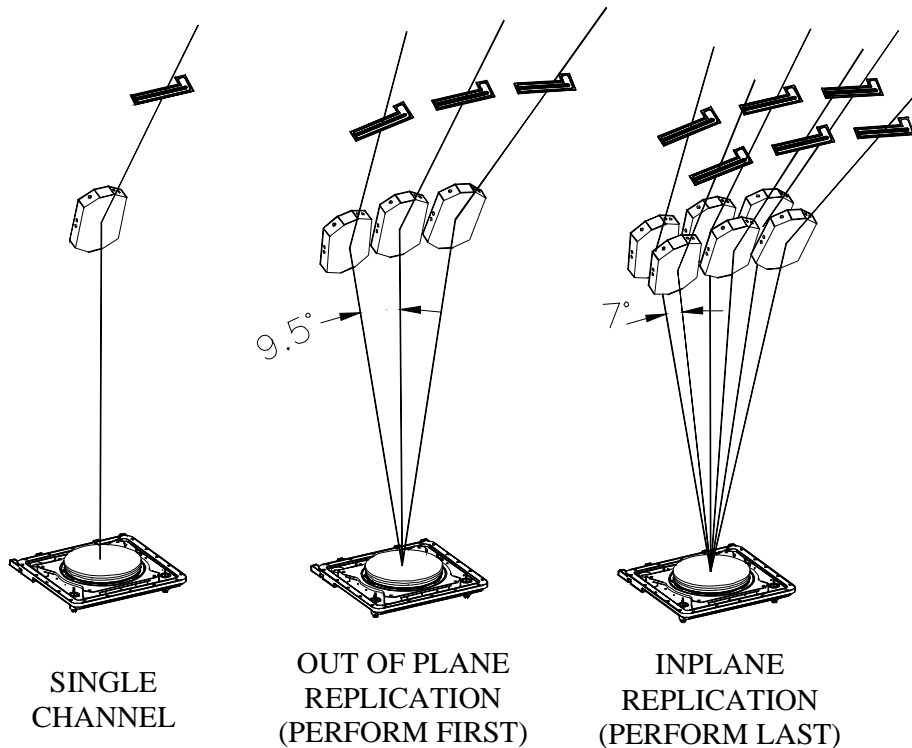


Figure 6: Channel replication order. Out of plane channel replication is performed first, followed by inplane replication of the resulting fan of three channels.

The key challenge in designing the CHIPS optical system was packaging the gratings to avoid light path obstruction, glints and physical contact between the channels, all while fitting within the allowable Delta-II and spacecraft volume. The minimum out-of-plane rotation angle about the spectral dispersion direction required to clear the adjacent channel, and allow mounting hardware, was $\sim 9.5^\circ$. Geometry allows a minimum rotation of $\sim 7^\circ$ in-plane to avoid shadowing the aft-located channel. Any spectrograph channel created by rotating first out of plane, then inplane, within the angular limits described above meets spectral

resolution requirements when aligned. This observation allowed the spectrometer to be manufactured with standard machine shop tolerances, albeit with considerable care taken during the alignment process. Details of the grating mounting scheme are discussed in⁵.

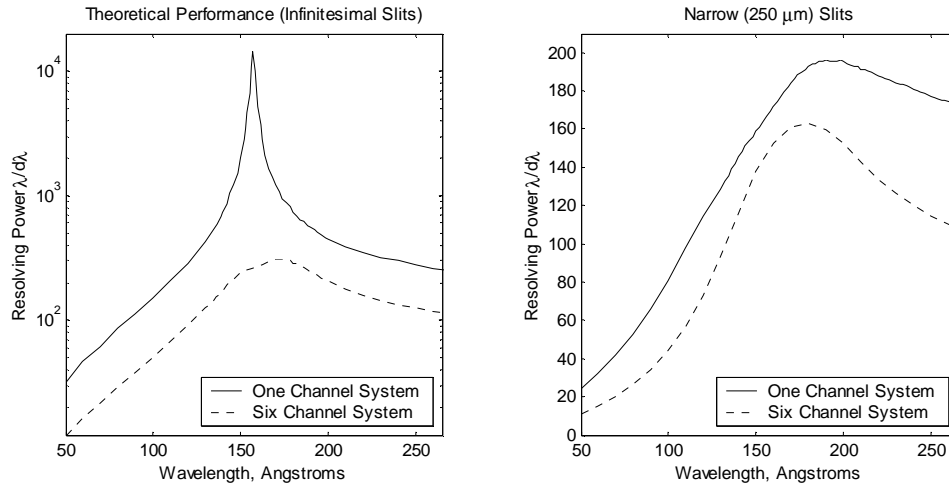


Figure 7: Performance Limits of CHIPS Optical System with infinitesimal and 250 μm slits, one and six channels.

The CHIPS MCP detector⁷ was adapted from those designed for the Galaxy Evolution Explorer, GALEX. CHIPS used an unsealed detector (in contrast to the sealed tubes of GALEX) and a NaBr photocathode on 75mm diameter MCPs with 12 μm pores oriented 13° from the focal plane normal. Details of the spring mount design trade study for the MCP support can be found in⁸. Stray and out-of-band light were reduced by panels of thin-film aluminum, polyamide boron, and zirconium filters located 8.8mm above the detector focal plane (See Figure 8). The detector vacuum chamber was opened on orbit with a one-shot Shape Memory Alloy (SMA) driven three-stage door release mechanism. During vacuum calibration, the door was re-closed using a geared DC brush motor driving a four-bar linkage, which closed the door and compressed the o-ring prior to backfilling the chamber. The time to digital converter was a low-power (Advanced CMOS comparator) adaptation of the emitter coupled logic (ECL) digitizer used on the NASA IMAGE FUV detector. Details of the novel delay line concept can be found in⁹.

3. THE QUEST FOR A VIABLE MISSION

A nine-channel variant of the instrument concept described in Section 2 was proposed in 1998 and selected for a UNEX phase A study. CHIPS was designed specifically to fly as a secondary payload on a Final Analysis FAISAT¹⁰ communication satellite. Final Analysis was founded in 1993 to provide global mobile wireless data services, and had an ambitious plan to launch a constellation of 26 moderate-rate data communication and store-and-forward satellites via a partnership with Polyot Inc. on the Russian Cosmos booster (a commercialized version of the SS-18 intercontinental ballistic missile, with small satellites instead of reentry vehicles mounted on the post-boost equipment section). The FAISAT satellite busses had a mass of 115kg, orbital altitude of 1000km and were gravity gradient stabilized with one reaction wheel included to point the solar arrays toward the sun. FAISAT-01 was launched in 1995, and FAISAT-02V launched in 1997. The CHIPS mission was designed to comply with the FAISAT Secondary Payload Program and collect data autonomously as the satellite orientation varied with the orbit of the spacecraft. The 26°x16° FOV of the proposed

mission, with nine channels and no pickoff mirrors, did not require precision pointing. An attitude knowledge of $\pm 1^\circ$ was made available to the CHIPS payload for pointing reconstruction during ground data processing. Figure 9 shows a FAISAT spacecraft bus (Source: www.finalanalysis.com).

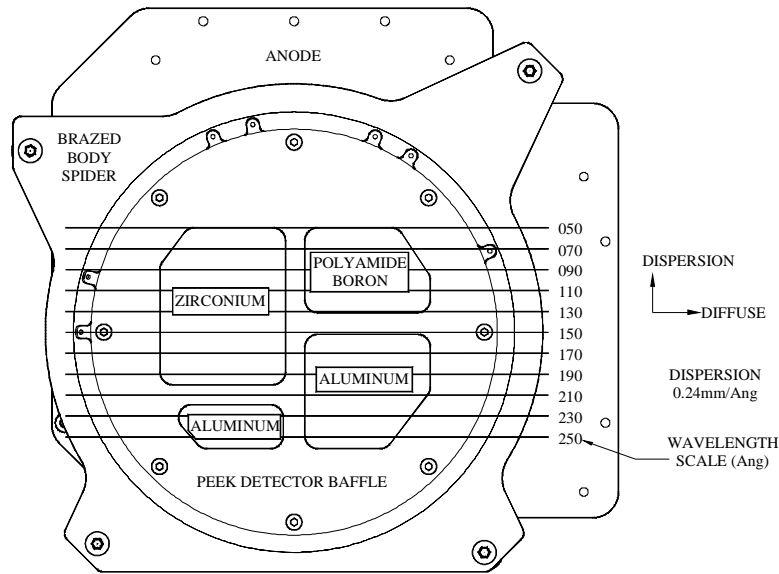


Figure 8: Detector filter frame. Thin ($\sim 1000\text{\AA}$) metal filters block out of band radiation.

Subsequent to selection of CHIPS for a Phase A study, in January of 1999, the Department of State invoked a 1994 law which precluded federally-funded missions from flying on foreign boosters^{11,12}. NASA informed the Berkeley team that CHIPS could not go forward in its FAISAT incarnation. The team approached a number of satellite providers about the possibility of including CHIPS as a secondary payload on a planned satellite, but without success. Subsequently, the team decided to develop a dedicated 3-axis microsatellite for CHIPS, and partnered with SpaceDev (Poway, CA) after reviewing proposals from several capable small satellite providers. This satellite was to have launched on the Shuttle Hitchhiker Ejectable Launch System (SHELS). Due to the low altitude of the shuttle orbit, a cold-gas propulsion system was baselined to raise the orbit of CHIPS.

During the Phase A study, due in part to safety concerns over flying a propulsion system on the shuttle and near the International Space Station, another launch opportunity as a secondary payload on a GPS satellite was identified. Due to the relatively large number of manifested GPS launches and concerns about uncertainties in shuttle launch schedules, the Delta-II/GPS combination appeared to be a less risky launch option for CHIPS. The spacecraft was to have fit in the SPE2 envelope, between the 2nd stage avionics and the outer skin of the launch vehicle¹³. The observatory was redesigned to fit into the SPE2 envelope, and is shown in Figure 10.



Figure 9: FAISAT spacecraft bus (photo courtesy of Final Analysis)

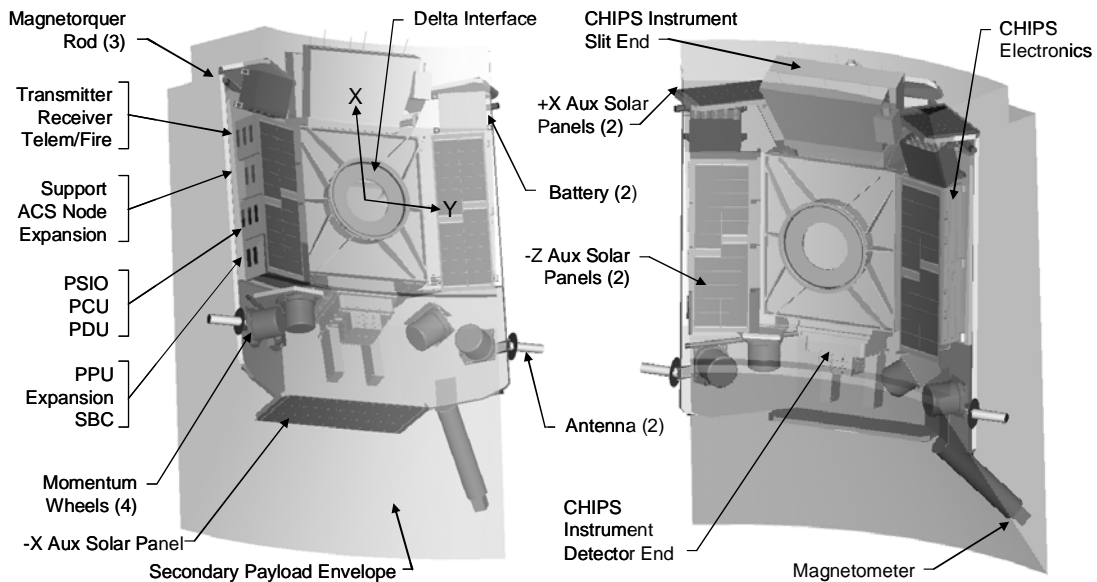


Figure 10: SPE2 envelope and CHIPS spacecraft concept compatible with Delta-II/GPS secondary payload accommodation.

Clampband moment restrictions required a reduction in the thickness of the observatory, and the optical design was descoped from nine to six channels. This resulted in a 33% reduction of the instrument throughput, which was offset to some degree by the increased noise rejection of Zirconium filters⁷ used instead of the polyamide/boron filters baselined in the proposal. An important lesson learned was that clampband moment requirements should be addressed in the mission concept phase, prior to detailed design, along with system mass budgets.

In late 2000, the team learned that the mass of the GPS satellite (with which CHIPS was scheduled to launch) could increase by 30kg, and eliminate the excess capacity that allowed CHIPS to fly as a secondary payload. Once again, CHIPS was in jeopardy of losing its launch slot and facing cancellation. After another extensive search for launch opportunities, the CHIPS team identified a viable launch slot (recently opened due to a project cancellation) as a secondary payload to the NASA/GSFC ICESAT mission. On September 6, 2001, the CHIPS team presented the concept to NASA in a Delta Design Verification Review. The GPS launch mass increase was reported publically several days later¹⁴.

The ICESAT secondary payload slot had ample volume and mass capacity for the original nine-channel spectrometer concept, but by this time design of the spectrograph and spacecraft had progressed sufficiently that a return to the nine-channel configuration would have increased overall mission cost and added risk to the already tight integration schedule for a dual-manifest launch with ICESAT. The decision was made to adapt the existing clampband design to the cancelled spacecraft's payload adapter. It's interesting to note that the cancelled mission was scheduled to launch on a Pegasus-XL originally, before co-manifesting with ICESAT. That project made a similar decision, and adapted their existing Pegasus-XL interface to the RHDPAF envelope. Figure 11 shows the unusual as-flown CHIPS payload attach fitting stack with interface adapters and accommodations for RHDPAF, Pegasus-XL and GPS/Delta-II SPE2.

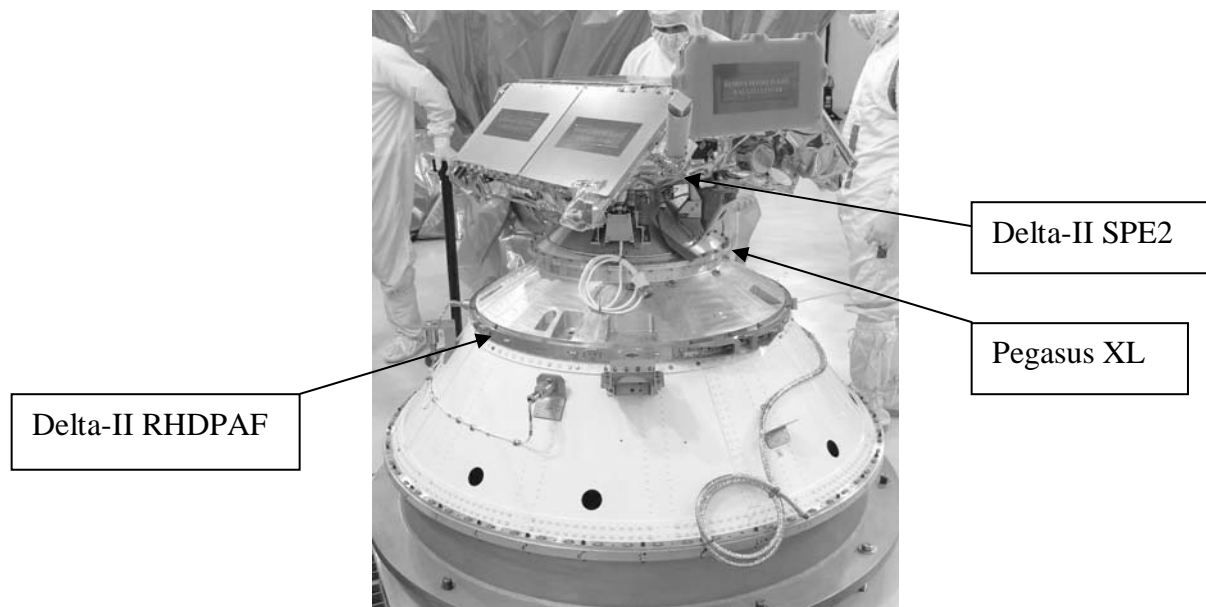


Figure 11: Due to the interesting challenges encountered en-route to launch, CHIPS launched with payload attach fittings for Delta-II Secondary Payload SPE2, Pegasus-XL and the Delta-II RHDPAF.

4. FABRICATION, ALIGNMENT, INTEGRATION AND TEST

Cost of a multi-channel optical system is reduced greatly by commonality and design reuse. Figure 4 shows in cross-section the light path from the slits to the detector. Channel replication (see Figure 6) leads to geometric blur, which increases the channel separation. The mechanical design challenge, constrained by the cost and schedule limitations of UNEX, boiled down to the following goals, solutions and lessons learned:

Design Goal	Solution/Reference	Challenges	Lessons Learned
Minimize separation between channels without mechanical interference or light blockage.	Main Optical Bench concept, see Figure 6, References ^{5,6}	Gratings contacted during vibration test.	Lateral channels contact at high vibration test levels. Test levels should be reasonable.
Use edge mounts on gratings; avoid back-side mounting.	Semi-kinematic edge mounts employed (beryllium-copper flexure blades), Reference ⁵		Flexure minimum thicknesses depend on buckling and yield margin requirements.
Minimize system cost via use of easily engineered materials (aluminum, instead of graphite cyanate ester or Invar).	Aluminum structure, open-backed Zerodur gratings, Reference ⁵ .		Strength of glass is determined mainly by surface properties.
Avoid structural adhesive joints and associated qualification and coupon testing.	Gratings mounted with fasteners, Viton, Teflon and stainless steel clamps, Reference ⁵ .	Grating alignment changed during vibration test.	Non-adhesive joints require a settling shake after initial assembly.
Grating mounts should be identical; Euler angle complexity should be in interface between grating mount and optical bench	Custom post/mounts between grating mounts and bench Reference ⁵ .	High dynamic amplification observed during vibration test.	When coupled with cantilevered design, these post/mounts should be made very stiff to increase overall natural frequency of gratings.
System signal to noise increased by spectrograph channel replication.	Six-channel configuration	Channel coalignment could only be verified during vacuum ultraviolet test.	Coalignment, and maintenance of coalignment between channels causes design and alignment of a multiple-channel spectrometer much more difficult than a single channel.
Maintain coalignment during thermal excursions.	Use aluminum structure and cantilevered grating and slit tower mounts. Reference ⁶ .		Cantilevered design rings "like a forest of tuning forks." Beware of dynamic amplification and Brinelling/fretting at joints.
Allow for alignment/coalignment at ambient conditions and visible wavelengths.	Use ruling spacing for visible light (HeNe laser, for example) on patches at extreme edge of gratings. Use a ground glass screen with a black thread/wire for alignment and coalignment. Use open (accessible) structure for visible alignment.		Visible patches require bright illumination (laser) and must be covered after alignment. Off-center yaw angles must be checked during visible wavelength alignment. Near and far visible ruling patches have different lever arms to detector (main tool for diagnosing misalignment). Theodolites and fiducials would have made alignment much less time-intensive.
Prevent fouling of microchannel plate photocathode	Process and launch spectrometer with detector at vacuum. Reference ^{6,7} .		A 1-shot door release mechanism necessitates a remote reclosing device for vacuum calibration.

Protect optics from contamination.	Purged optics chamber, leaky slit mechanisms, custom T-0 purge mechanism designed	Launch vehicle providers balk at T-0 (disconnects at liftoff) purge.	T-0 purge is practical, and should be baselined if needed.
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5. STRAY LIGHT, SNEAK PATHS AND SERENDIPITY

Subsequent to the baseline mission, the CHIPS spectrograph was used for ancillary science and targets of opportunity. EUV emissions from three nearby comets were studied¹⁵. Pointed observations were carried out near the sun, and an interesting and unexpected spectral profile was observed¹⁶. The appearance was found to be repeatable when the spectrograph boresight was pointed roughly 24° from the sun. Flux levels were much higher than expected from Zodiacally scattered radiation. A detailed examination revealed a possible source of the spectra. A baffle, placed within the slit wheel to block the direct sneak path to the grating on the pickoff mirror channels, was (by design) visible to the grating. When the spectrometer was pointed toward the sun, interior surfaces of the slit wheel (including the sneak path baffle) were flooded with direct and reflected sunlight. The illuminated baffle (see Figure 12) was directly visible to the grating, and provided scattered solar radiation to the three mirrored spectrograph channels.

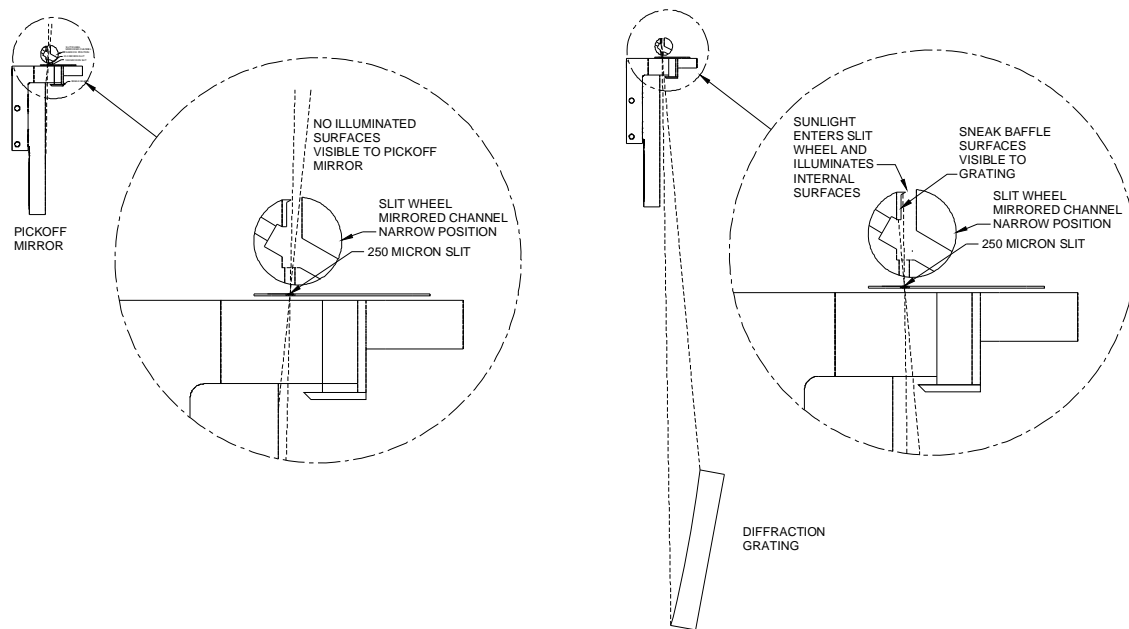


Figure 12: When the spectrograph was pointed near the sun, bright solar spectra appeared unexpectedly. As shown on the left figure, no illuminated surfaces were visible to the pickoff mirrors. Interior surfaces of the slit wheel, including a sneak baffle (figure on right) were both illuminated by sunlight (via scattering) and visible to the grating.

CONCLUSIONS

CHIPS launched on 12 January 2003, and was the first and only successful GSFC UNEX (NASA Goddard Spaceflight Center University Explorer class) mission. The observatory operated for five years, and was placed in an extended safe-hold mode in April, 2008 for budgetary purposes. In addition to the baseline science, solar spectra were observed via illumination of a sneak ray baffle. The CHIPS team overcame numerous difficulties, and proved the basic tenet of the UNEX program, namely that with a dedicated team and sufficiently limited mission scope, low cost orbital science missions are possible at the university level.

The CHIPS optical and optomechanical systems operated flawlessly on orbit, and disproved contemporary theories on the local bubble.

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