HIGH-RESOLUTION IMAGING OF THE UPPER SOLAR CHROMOSPHERE: FIRST LIGHT PERFORMANCE OF THE VERY-HIGH-RESOLUTION ADVANCED ULTRAVIOLET TELESCOPE

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Abstract. The Very-high-resolution Advanced ULtraviolet Telescope (VAULT) experiment was successfully launched on 7 May 1999 on a Black Brant sounding rocket vehicle from White Sands Missile Range. The instrument consists of a 30 cm UV diffraction limited telescope followed by a two-grating, zero-dispersion spectroheliograph tuned to isolate the solar Lα emission line. During the flight, the instrument successfully obtained a series of images of the upper chromosphere with a limiting resolution of ~ 0.33 arc sec. The resulting observations are the highest-resolution images of the solar atmosphere obtained from space to date. The flight demonstrated that sub-arc second ultraviolet images of the solar atmosphere are achievable with a high-quality, moderate-aperture space telescope and associated optics. Herein, we describe the payload and its in-flight performance.

1. Introduction

A key to observational progress in understanding solar atmospheric heating over the last 30 years of solar physics has been the ever-increasing spatial resolution of spectroscopic instrumentation. NRL pioneered high-spatial-resolution observations in the far ultraviolet with the High-Resolution Telescope and Spectrograph (HRTS) (Bartoe and Bruecker, 1975). HRTS observed the structure and dynamics of the solar atmosphere with high spatial and spectral resolution over 10 sounding rocket flights and the Spacelab 2 mission. A primary topic of investigation was the study of flows and ejections in fine-scale structures (Brueckner and Bartoe, 1983; Dere *et al.*, 1991; Dere, 1989). These studies demonstrated the highly dynamical physics of the solar chromosphere and transition region in small spatial scales and indicated the existence of even finer sub-resolution structures. The small fill factor of transition region structures (Dere *et al.*, 1987) is a further indication that the 'fine' (< 3 arc sec) structures seen by HRTS are composed of filamentary structures with radii of the order of 100 km. There is also significant theoretical work on coronal heating mechanisms that invokes small-scale phenomena (e.g., Rabin

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and Moore, 1984; Van Ballegooijen, 1986; Einaudi *et al.*, 1996; Hendrix and Van Hoven, 1996). It is apparent that even higher spatial resolution observations are critically important to further advances in understanding the fundamental physics of the solar atmosphere, especially plasma heating mechanisms.

To address these scientific questions, we developed the Very-high-resolution Advanced ULtraviolet Telescope (VAULT), a new spectroscopic imaging instrument which is described in detail in Sections 2 and 3. The instrument was successfully launched on 7 May 1999 as a sounding rocket payload. The goal of the VAULT flight was to obtain sub-arc second images of the Sun in the light of Lα. VAULT directly imaged the fine-scale chromospheric structures within supergranule boundaries, the network, and active region plage and filament channels with resolution never achieved before from space. These images and some preliminary results are presented in Section 4. We conclude with our plans for the next flight in Section 5.

2. VAULT Instrument Description

The payload makes extensive use of existing HRTS hardware and mechanical design heritage. The overall mechanical design of VAULT is identical to the HRTS. The latter has benefited from several experience-based modifications over the years, particularly in the telescope design area, and meets the VAULT performance objectives. The telescope tube and focal plane deck structure are cantilevered from a central bulkhead. The primary mirror is potted in a central hub, to avoid stressing the optics. Curing procedures, which effectively avoid molecular contamination, have been developed. The hub is mounted directly to the central bulkhead. The focal plane deck structure is launch-locked to the rocket skin using a retractable pin mechanism. The front and aft rocket skins are bolted to the central bulkhead. A vacuum compatible and controllable aperture door is provided by the NASA Wallops Flight Facility and is used to expose the telescope to the Sun and to protect it from damage during reentry. A pair of specially designed breather filters on the telescope door slowly bleeds the instrument to ambient pressure while the payload is descending to the desert floor. VAULT reuses the front and aft HRTS skins from HRTS 8 and 9, but a new vacuum bulkhead and electronics section were fabricated for VAULT.

The principal components of the VAULT are presented in Figure 1. The VAULT optical train consists an excellent optical quality (λ/16 r.m.s. at 1215 Å), 30 cm diameter telescope followed by a zero dispersion spectroheliograph (Bartoe and Bruecker, 1975). The Lα solar image is focused onto a lumogen coated Kodak 6301 9 μm pixel CCD. The CCD format of 2048 $\times$ 3072 pixels allows a field of view of 4.3 arc min $\times$ 6.4 arc min with a 0.125 arcsec pixel^{-1} pitch. At ultraviolet wavelengths, the 30-cm diameter aperture telescope of the instrument is potentially capable of a much higher spatial resolution than 1 arc sec. Figure 2

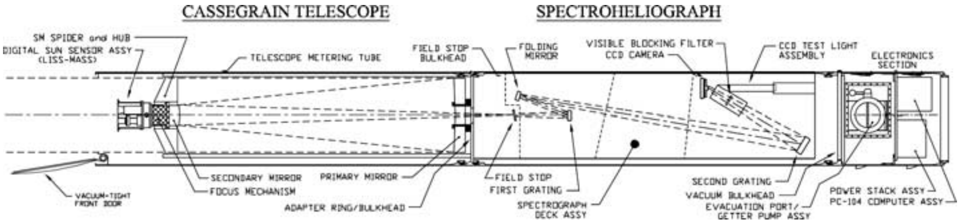

Figure 1. VAULT optomechanical layout. Solar radiation enters the telescope through the commandable vacuum door. The primary mirror forms a virtual solar image behind the telescope secondary mirror. The secondary mirror produces a real image of the solar disk at the spectroheliograph field stop. The light passing through the field stop is dispersed and collimated by the G1, a Wadsworth collimator. The UV radiation is incident on the folding mirror and the second grating. The second grating then produces a zero dispersion image of the solar disk with a geometrically defined bandpass of 150 Å. This bandpass is determined by: (1) the size of the second grating, (2) the spectral dispersion of the first grating and (3) the distance between the first and second grating. The second grating is mounted as an inverse Wadsworth collimator. A visible-light rejection filter is placed just in front of the CCD camera. The figure also shows the digital version of the Lockheed Intermediate Sun sensor in the front of the payload. The vacuum evacuation port and the two main electronics boxes are shown at the rear of the payload.

shows the ideal ultraviolet MTF of a 30-cm telescope at Lα λ1215 Å. The VAULT instrument is specifically designed to operate near the Lα Rayleigh diffraction limit ($\sim$ 0.1 arc sec) with an angular resolution of 0.33 arc sec. The solar radiation passing through the field stop, is collimated and dispersed by G1, reflected by a single folding mirror and recombined by G2. The G1 and G2 grating configuration was selected to obtain a UV solar image with minimal geometric blur ($<$ 5 μm, 0.07 arc sec, predicted by a ray trace and confirmed during laboratory testing), moderate bandpass (150 Å at Lα) and high efficiency ($\sim$ 13%). A narrow-band VUV filter located just in front of the CCD rejects the remaining visible radiation. The CCD UV quantum efficiency ($\sim$ 10%), linearity and dynamic range are substantially improved over the 101 film used in the past. The throughput allows short exposure times even with a plate scale of 72 μm arc sec^{-1}. The plate scale of the image is 0.125 arc sec pixel^{-1} which allows more than two pixels for each resolution element. As an example, Figure 3 shows a focus test image taken in the laboratory of a USAF target placed at the field stop.

VAULT uses an f/24.6, 30 cm diameter, 25% obscuration Cassegrain telescope. The parameters were chosen to allow reuse of the HRTS Gregorian graphite tube and structure. While prior HRTS Cassegrain and Gregorian telescopes had f/3 primary mirrors with a secondary mirror magnification of 5, VAULT uses an f/4.92 primary with a magnification of 5. The thermal loading of the Zerodur primary and secondary is similar to the HRTS rocket Cassegrain. The VAULT produces a solar image with a plate scale of 72 μm arc sec^{-1} compared to the HRTS value of 22 μm arc sec^{-1}. Coma and astigmatism are $<$ 0.01 arc sec over the instrument field of view. The slower primary mirror reduces the sensitivity of the telescope to secondary decenter, focus and tilt. The telescope tube and structure have been

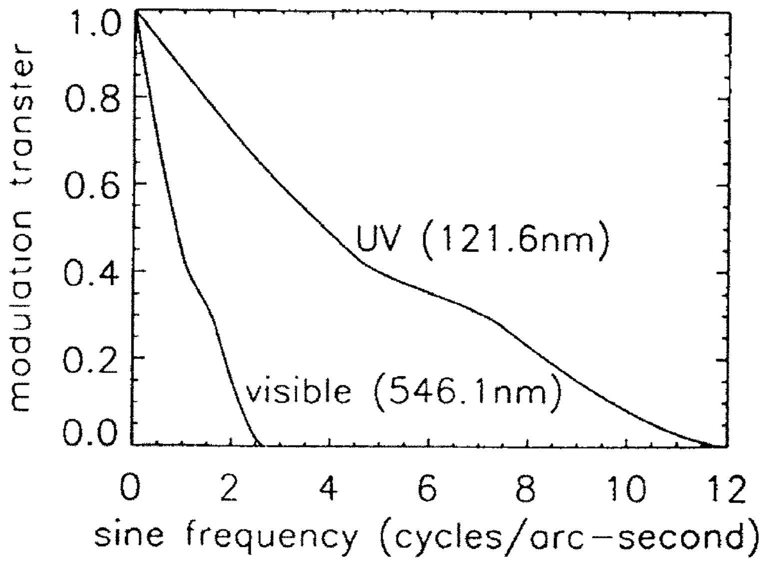

Figure 2. Diffraction limited sinusoidal MTF function plotted for a 30-cm telescope with 25% obscuration at λ5461 Å and λ1215 Å.

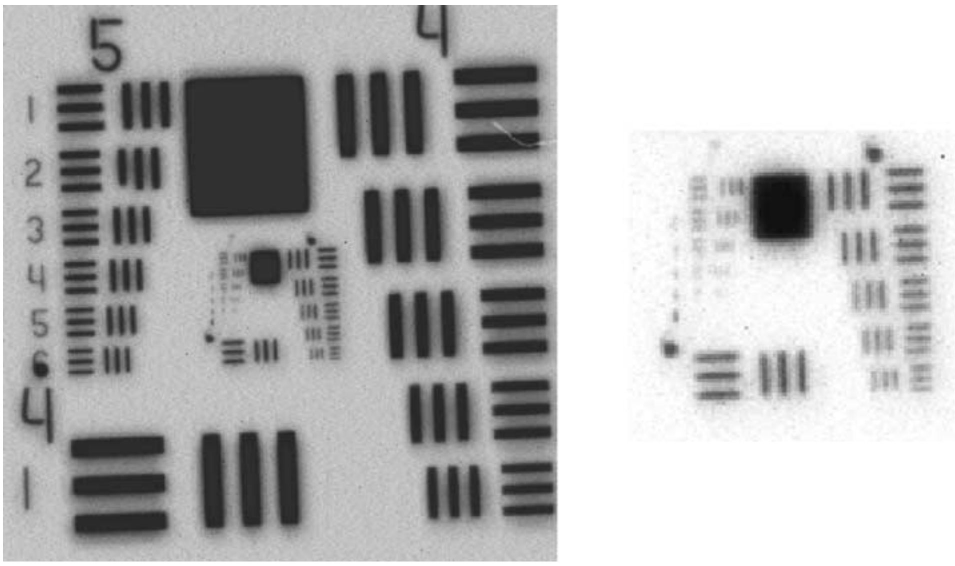

Figure 3. Left panel: image from a VAULT focus test using the USAF resolution target. *Right panel*: enlargement of the central area of the target. The smallest vertical stripes that can be resolved correspond to the desired 0.25 arc sec or two-pixel resolution.

flown on *Spacelab 2* as well as HRTS 8 and 9. The maximum observed amount of tilt and decenter in the telescope has been observed to be <1 arc sec and < 50 μm, respectively, even under relatively severe stress conditions. The amount of blur induced by this secondary tilt and decenter is < 0.05 arc sec. The combined telescope system optical/mechanical performance allows 0.33 arc sec spatial resolution to be achieved.

The superb, demonstrated performance of the Mark-7 SPARCS attitude control system allows VAULT and other high-resolution solar payloads to be launched without image motion compensation systems. The new system incorporates a fiber-optic communication line that relays the sensor output information to the ACS system. The new electronics includes a microprocessor for digital control of the SPARCS gas jets. The performance of the SPARCS system during the VAULT flight was superb. The drift and jitter, generally associated with electrical pickup on the signal lines in the long cable between the SPARCS skin section and the analog sensor, were entirely eliminated. Over a relatively short time period (a few seconds), a stability of the payload of 0.2 arc sec was obtained. The overall performance of the system was excellent. During the flight, we did encounter significant drift between the sensor axis and the experiment axis. The drift appears to be thermally driven. For the second flight, we will mitigate the drift by restricting the solar illumination of the telescope structure and adjusting the thermal properties of the sensor faceplate.

3. CCD Camera and Flight Computer Description

A block diagram of the VAULT electronics bulkhead is shown in Figure 4. A PC-104 computer sequences the mechanisms, the CCD camera and the telemetry interface. A number of auxiliary boards provide power conversion, internal/external power relays, analog conditioning and mechanism driver functions. The computer is comprised of Commercially available Off The Shelf (COTS) PC 104 format boards; these boards are repackaged at NRL to withstand the sounding rocket environment. The small footprint (90×90 mm), low power dissipation and surface mount PC 104 format boards are technically well suited to the sounding rocket application; the boards are also readily available and reasonably priced. The computers are used routinely in embedded systems; the DOS and BIOS of these computers are specially modified to prevent fatal operating system errors. In addition to these precautions, the computer board selected for VAULT has a hardware watchdog timer. The flight sequences are programmed in ‘C’. The parallel interface to the telemetry section is with a custom PC-104 format, FIFO card.

The CCD camera is a repackaged version of the COTS AP-9 Apogee camera. These cameras have proven performance in a wide variety of scientific applications; a modified Apogee camera is scheduled for flight in a Shuttle payload. The VAULT camera incorporates a Kodak 6301, grade-3 CCD detector. The CCD is

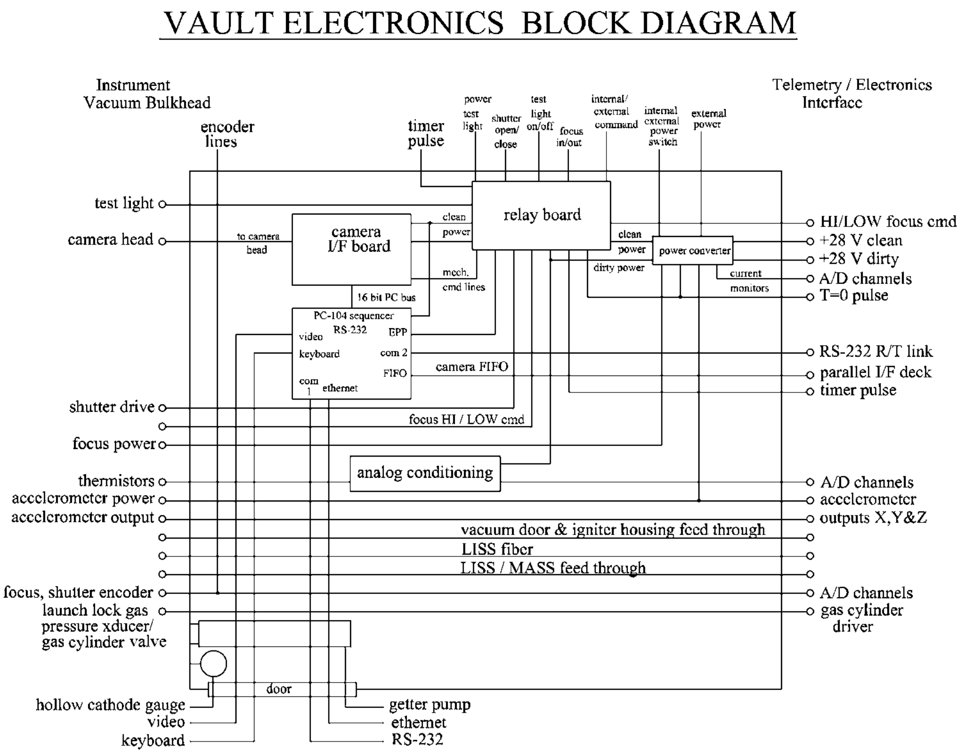

Figure 4. The diagram shows the major electronic components of the VAULT electronics skin section. The electronics are comprised of two boxes. One box houses the PC-104 computer and camera controller card. The second auxiliary electronics box contains the junction board, analog signal conditioning board, mechanism driver board and power converters. The electronics skin section was designed to allow operation of the mechanisms and computer stack through the umbilical in a stand alone configuration.

lumogen coated to obtain ultraviolet sensitivity. Existing software drivers for the commercial camera were used as the building blocks to construct the VAULT flight and laboratory software.

4. In-Flight Performance of the VAULT Instrument

The VAULT payload was successfully launched on a Black Brant sounding rocket from White Sands Missile Range on 7 May 1999. The payload obtained Lα images of the solar chromosphere from two pointing positions. A combined image of the two pointing positions is shown in Figure 5. The exposure times during the flight varied from 2–6 s. We obtained a total of 17 solar images with a cadence of 22 s and one dark frame. The field of view included part of NOAA active region 8525, a large filament and quiet-Sun areas. Figure 6 shows the large-scale chromospheric structures imaged by the payload. Figure 7 shows a series of progressively magni-

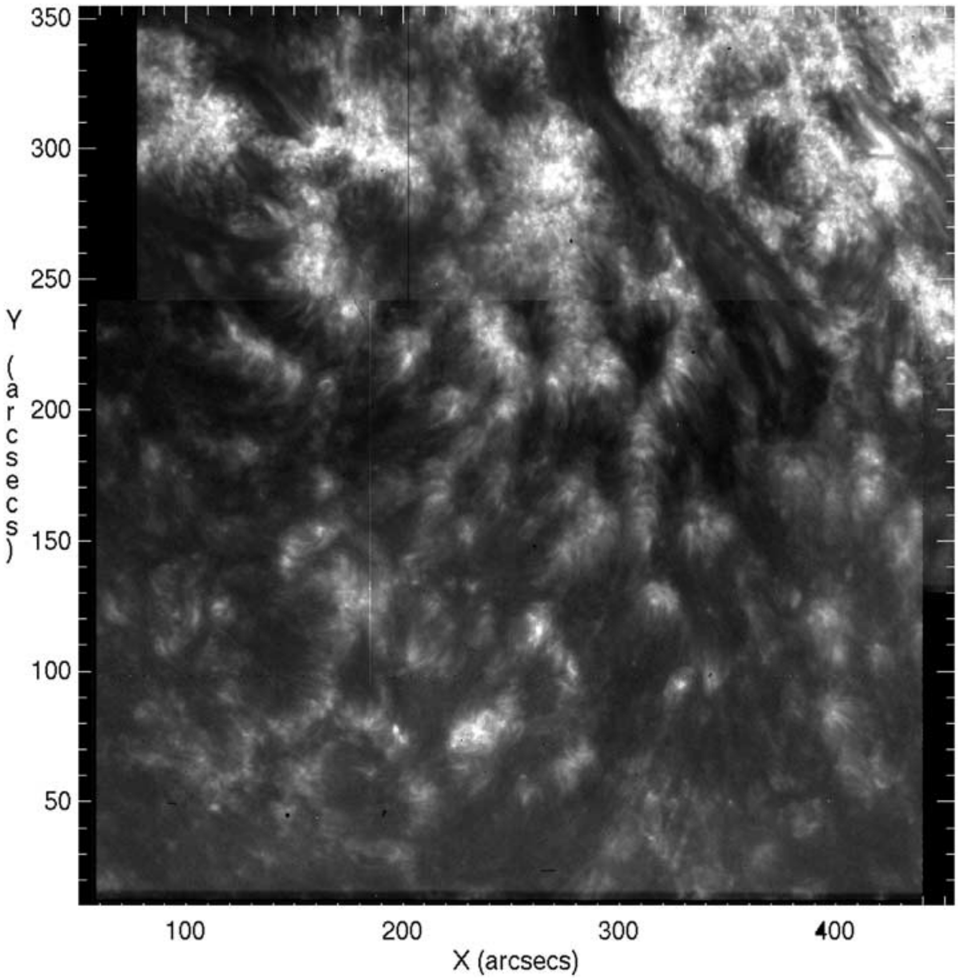

Figure 5. Composite of the two point positions during the first flight of the VAULT payload. The target was AR 8525. Both active region and quiet-Sun areas were imaged. The axes denote distance from the Sun center. The dark/bright vertical lines correspond to a saturated column.

fied images. The smallest structure in these images is ~ 0.33 arc sec. The sequence of images clearly shows that the chromosphere is highly dynamic and continuously evolving. The fine scale structure in the upper chromosphere consists of loop-like filamentary structures and bright knots. The footpoints in the majority of the Lα loops seem to be in continuous motion and flows along the loops themselves are frequent. The flows have lifetimes of the order of one minute. At the same time, small-scale brightenings in the shape of knots appear everywhere; in the quiet Sun, in areas between loops and inside the filament. We have not yet determined their brightness and therefore we cannot say if they classify as nano-flares but their lifetimes are of the order of 1–2 min. Another interesting observation, are

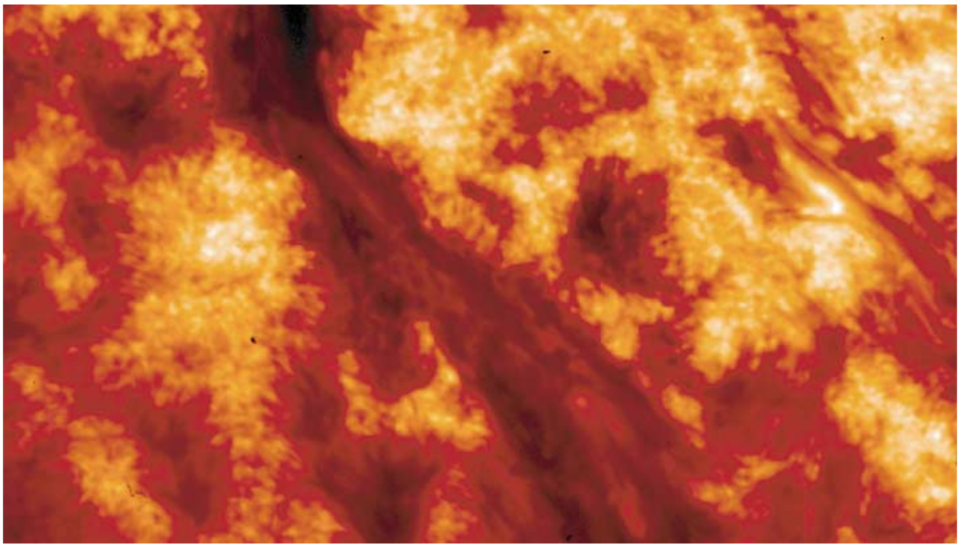

Figure 6. Detail from the previous image. The image size is 158 × 88 arc sec. A large filament surrounded by active region network is clearly seen. An active filament channel is visible at *the upper right corner* of the image.

the bright filamentary structures embedded in the large, dark Hα filament (Figure 3). They are so numerous that the filament is mostly emitting in Lα rather than absorbing, as is usually seen in Hα observations of filaments. The correlation of these chromospheric structures with photospheric magnetograms and coronal structures imaged with the Michelson Doppler Imager, the Transition Region and Coronal Explorer and the Extreme ultraviolet Imaging Telescope experiments is being explored. The results will be published in a separate paper.

5. Conclusions

The 0.33 arc sec spatial resolution of VAULT is on the order of the predicted scale lengths of dissipative processes in the solar atmosphere, the mean free path of Lα photons, the spatial scales associated with the underlying photospheric granulation, and predicted diameters of magnetic flux tubes. The VAULT images of the upper chromosphere and transition region, obtained at unprecedented spatial resolution in the ultraviolet, reveal a highly dynamic chromosphere comprised of interacting fine scale loops and bright knots. The active region plage is comprised of interacting, fine scale loop structures undergoing continuous evolution. The rearrangement of these structures is consistent with an explanation of footprint driven magnetic reconnection or possibly sporadic heating/injection of material. The filament channel contains a network of light bridge like structures. The observed structures have finer resolution than available magnetograph and coronal images from present or-

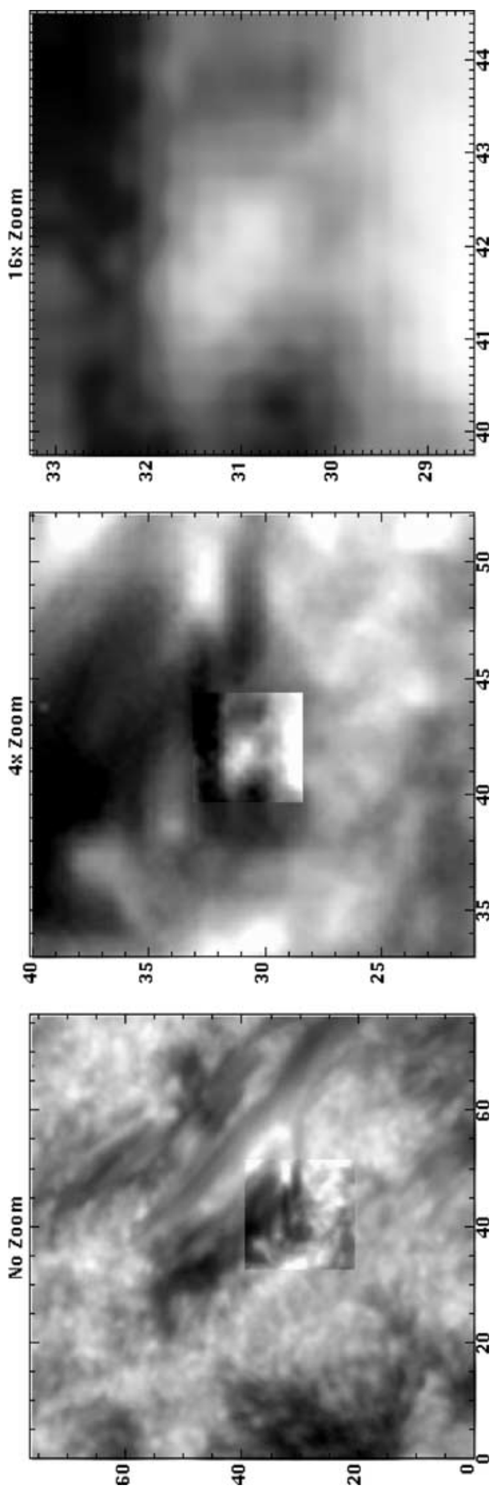

Figure 7. The figure shows successive magnified images of an area close to a filament channel. The area inside each box is magnified by a factor of four in the subsequent image. The original VAULT data was binned to 0.3 arc sec pixels in the first image. The last image demonstrates that fine scale structures of < 0.5 arc sec are readily visible in the VAULT data. The axes are labeled in arc sec.

biting instrumentation. These images are the highest resolution images of the solar atmosphere obtained from a space instrument to date. The next flight of the VAULT instrument is scheduled for the spring of 2001. We plan an observing sequence similar to the one in the first flight. For this flight, we will increase the instrument throughput by using improved versions of the current Lyα filter and CCD camera. Several other upgrades are also in progress. With these improvements, we hope to obtain images with improved SNR and even higher resolution than the ones presented herein.

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