

Large scan mirror assembly of the new Thematic Mapper developed for
LANDSAT 4 earth resources satellite

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Abstract

This paper reviews mechanical aspects in the development of a large, oscillating scan mirror mechanism that featured a remarkably low level of structural vibration for the impact energies involved in mirror oscillation. Another feature was that energy lost during impact was returned to the mirror by applying torque only during the instant of impact. Because the duration of impact was only about 0.010 second, it was critical that energy losses be minimal since there was not much time to restore them. Solutions to these critical mechanical problems constituted a major milestone in the development of object-space scanning sensors.

Introduction

Early in the space program, NASA recognized the importance of remote sensing for management of the earth's resources and human environment. This recognition led to the formation of a program, later named LANDSAT, under the management of the Goddard Space Flight Center of NASA with a purpose of sensing data for such diverse applications as agricultural and forestry inventories, oil and mineral exploration, hydrology, geology, and land use inventory. For that purpose, the new Thematic Mapper scanning sensor can give nearly complete optical coverage of the earth from an altitude of 705 km. As a spacecraft progresses southbound in a near polar orbit, object-space scanning is accomplished by a mechanical scanning flat mirror that sweeps the optical line of sight from side to side, easterly and westerly.

The Thematic Mapper sensor, which was launched on 16 July 1982 aboard the LANDSAT 4 spacecraft, has provided spectacular imagery. Scenes of the earth with 30 m resolution show small roads and residential districts with remarkable clarity.

This paper discusses the Thematic Mapper sensor, puts particular emphasis on the solution to the critical mechanical requirements imposed on the scanning mechanism, and, finally, presents a scene of the earth taken from an altitude of 705 km.

Description of mechanism

As a spacecraft progresses southbound in a near polar orbit, scanning is accomplished by a mechanical oscillating flat mirror that sweeps the optical line of sight from side to side as illustrated in Figure 1. This enables a 185-km-wide swath of the earth to be viewed during each orbit. A series of orbits can completely map the entire earth, except for small areas around both poles, every 16 days.

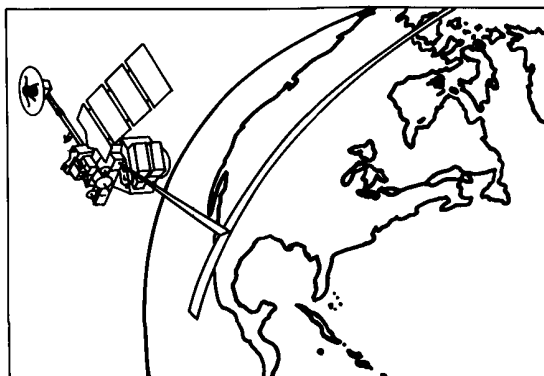


Figure 1. Thematic Mapper sensor mounted on LANDSAT 4 spacecraft showing orbit and scan pattern

The sketch in Figure 2 shows the elements of a Thematic Mapper sensor in relation to the orbit. Reflective optics focus visible and infrared energy from the earth onto detectors that are sensitive to designated spectral bands. Earth is downward, and the spacecraft velocity vector, which is nominally southbound, is moving away from the reader. Oscillating the scan mirror $\pm 3.85^\circ$ causes the optical line of sight to sweep $\pm 7.70^\circ$ back and forth across the 185-km swath of earth. This enables the sensor to view a swath of the earth during each orbit. In this system, the scan mirror sweeps first in one direction, then back in the other, imaging data during both passes. Earlier systems imaged data during only one pass and were inactive during retrace. Scanning bidirectionally increases scan efficiency. In addition to such efficiency, earlier sensors lacked the resolution and radiometric accuracy of Thematic Mapper. The entire Thematic Mapper sensor is illustrated in Figure 3.

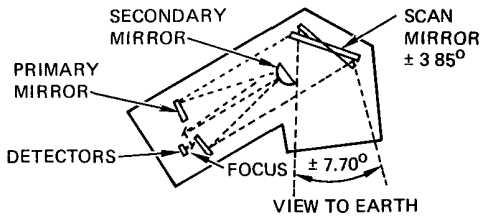


Figure 2. Simplified schematic of Thematic Mapper sensor

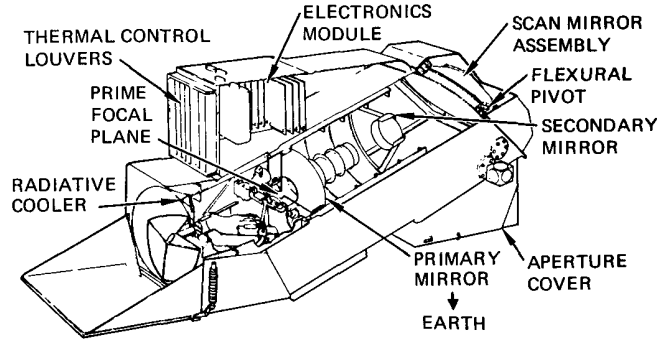


Figure 3. Thematic Mapper sensor

The scan mirror assembly (Figure 4) is a key element of the Thematic Mapper system. It provides the benefits of object-space scanning by means of an ultra-lightweight, brazed beryllium mirror and a patented scan mirror concept which meets the very stringent requirements placed on vibration, coefficient of restitution bumpers, scan linearity, as well as optical properties such as MTF and band-to-band registration. The scan mirror assembly consists of an optically flat 16 by 20-inch elliptical scan mirror mounted by Bendix flexural pivots to a fixed frame, an electromagnetic torquer, leaf spring bumper assemblies, an optical position sensor, and drive electronics. The scan mirror oscillates by rebounding between the bumper assemblies in a bang-bang manner and scanning between rebounds at nearly constant angular velocity. During the 0.010-second of impact, the torquer adds the energy needed to maintain a constant 7-Hz oscillation; see Figure 5 for scan parameters. Mapping accuracy as well as data transmission and processing dictate the need for a nearly constant scan rate. Since torque affects scan rate, restoring torque can be applied only during those moments of turnaround when data is not being taken. This requirement for torquing only during turnaround was a major consideration in designing the bumpers, since it dictated the need for an extremely high coefficient of restitution. In earlier systems, energy was restored by torquing during the entire return pass; hence, bidirectional scan was never before possible.

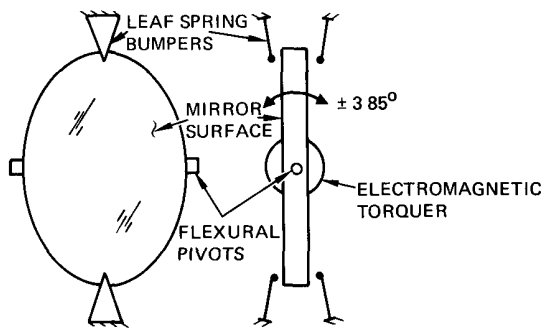


Figure 4. Thematic Mapper scan mirror assembly

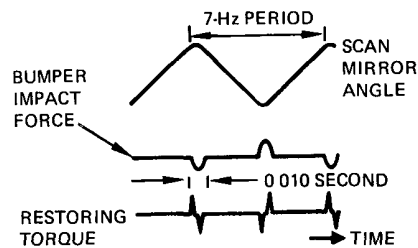


Figure 5. Scan mirror parameters

Each bumper consists of a leaf spring preloaded against a polymeric stop (see Figure 6). When the mirror impacts a spring at turnaround, the spring is deflected away from the stop; after turnaround, the stop damps out spring vibration before the next turnaround. The stop is made of DuPont Viton. Another polymeric material (Delrin AF) of a particular radius is bonded to the spring tip. The radius, which contacts a hardened steel pad bonded to the scan mirror, is carefully selected to minimize sliding and maximize rolling of the contact surfaces. Hence, the rolling radius both increases the coefficient of restitution and reduces bumper wear. As is described later, this bumper configuration was selected for reasons of vibration and energy loss.

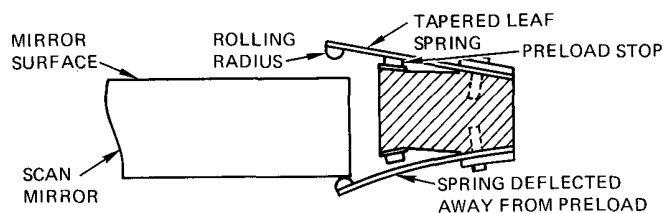


Figure 6. Bumper assembly

One of the key technology issues in this program was the development of an ultralight-weight, brazed beryllium scan mirror. This mirror, an optically flat, 16 by 20-inch ellipse, was made of two 0.070-inch facesheets brazed onto a 1.50-inch deep eggcrate core. The core consisted of 0.020-inch thick cell walls spaced on a 0.75-inch square pattern. Facesheets and core were entirely beryllium. The mirror itself weighed only 4.1 lb. Mirror weight was critical because of its effect on vibration, momentum transfer to the spacecraft, torquer power, and launch stresses in the flexural pivots.

Because the flexural pivots have a torsional stiffness which tends to accelerate the scan mirror far in excess of the requirements for scan linearity, it was necessary to employ a negative spring composed of magnets carefully adjusted to almost exactly cancel the positive stiffness of the flexural pivots. Since the attraction between magnets having opposite polarity tends to increase as the separation between them decreases, orienting a pair of magnets on each side of the flexural pivot creates a device which possesses all the characteristics of a spring with negative torsional stiffness. Designing this spring to have the required linearity involved a very complicated synthesis of geometry and magnetic fields.

The performance of this scan mirror assembly was measured with an interferometric angle-resolving system which had a resolution and repeatability of 0.4 μ rad and an accuracy of approximately 3 μ rad. This system counted fringes up and down at a rate in excess of 5 million fringes/sec and even maintained an accurate count throughout the high-frequency vibrations that occurred during bumper impacts.

Design requirements

The principal mechanical design requirements were minimization of structural vibration and minimization of energy loss during turnaround. Specifically, it was required that:

- The total angular vibration of the mirror be less than 2 μ rad peak-to-peak during operation at 7 Hz. This was a relatively small level of vibration for the impact energies involved in the mechanism. By comparison, the angular vibration of the previous-generation system, the Multispectral Scanner, was 40 μ rad peak-to-peak and that system had a smaller scan mirror. The most significant mode of vibration was that of the mirror vibrating as a mass suspended on two springs, each spring representing the shear stiffness of the flexural pivots. This requirement arose from the rather exacting pointing and timing specifications.
- The coefficient of restitution of the bumper springs be sufficiently high that energy losses could be restored by operating an electro-magnetic torquer only during the 0.010-second turnaround. This requirement arose from the fact that torquing at any other time would affect scan linearity. Also, there were limits to the amount of energy that could be provided in 0.010-second by even a relatively large torquer.

Discussion

Structural vibration

Bumpers were located at each end of the scan mirror in order to reduce the force on the flexural pivots during turnaround to, in the ideal case, zero. Actually, of course, pivot forces could not be completely eliminated. Nevertheless, it was important that they be minimized because they tended to excite vibrations of the mirror on the pivots; this meant that bumper locations had to be carefully adjusted. These adjustments were monitored by observing signals from magnetic pickoffs that measured bumper spring motion.

Experiments with a breadboard model revealed that carefully locating the center of gravity of the scan mirror by adjusting a movable mass had little effect on reducing vibration. It therefore became apparent that an entirely different approach must be taken. The approach which proved to be very effective in reducing vibration was to design bumpers in such a way that the frequencies of the impact forces were compatible with (i.e., distinct from) the natural frequencies of the system.

The vibration of a structure is a strong function of the frequencies of the excitation forces; in this mechanism, the excitation frequencies were the result of the impact of the mirror on the bumper springs. Consequently, reducing the general level of vibration involved thoroughly understanding the impact dynamics and evolving a bumper design such that impact frequencies were safety distinct from all natural frequencies of the system.

Figure 7 is a schematic of the scan mirror assembly together with a simplified mathematical model that is very useful in understanding the dynamics of the impact forces. Measurements of spring velocity indicated that, to first order, the approximation was very realistic.

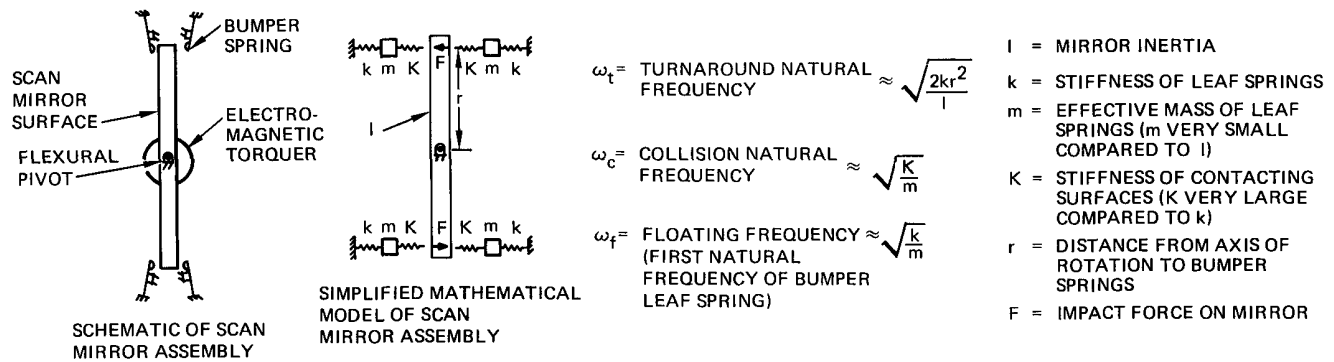


Figure 7. Impact dynamics

At turnaround, the mirror impacted bumper springs, which possessed some small mass. Therefore, in addition to the fundamental turnaround frequency ω_t that would have existed had the springs been ideal and massless, a higher frequency, due to the two colliding masses, was introduced at the moment of impact. Before the collision, the spring mass was at rest, and the mirror was approaching at its scan velocity. After the collision, the spring tip rebounded off the mirror, floated away from it, then floated back toward the mirror and collided with it again. This process was repeated until, after a series of collisions, it was damped out by surface friction. The natural frequency of the collision ω_c was approximately equal to $\sqrt{K/m}$, which states that in the collision, the spring tip mass m rebounds off the mirror and relies upon deformation of the contacting surface stiffness K to store energy during the collision. This type of collision is similar to that of a plastic sphere dropped on a steel plate. The frequency at which the spring tip mass floats away from the mirror is the first natural frequency of the bumper spring. In the simplified model, this frequency $\omega_f = \sqrt{k/m}$, as indicated in Figure 7.

The net results of the impact dynamics was that during turnaround, a force (Figure 8) was produced at each end of the mirror. This force consisted of essentially two kinds of components, viz., a low-frequency component, which was due to the stiffness of the bumper springs, and a high-frequency component, which was due to spring tip mass and occurred at the start of turnaround.

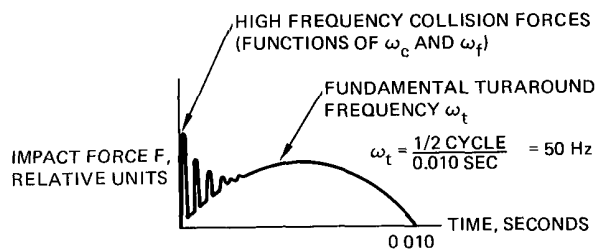


Figure 8. Impact force

One basic conclusion drawn from the model was that impact frequencies were primarily the result of bumper spring properties, viz., leaf spring mass and stiffness, and surface contact stiffness. Therefore, all those properties were varied by testing several bumper designs until one eventually was developed for which all of the impact frequencies were either well above or well below the significant natural frequencies of the system. For example, the 50 Hz turnaround force was well below the 95 Hz lowest mode of the support structure, and the approximately 2,000 Hz collision forces were above the highest natural frequency of concern, which was a plate frequency of the scan mirror. Testing was very useful since the collision forces depended somewhat on very sensitive microscopic surface phenomena, such as friction, stiction, and wear.

This theory led to the bumper design described earlier and illustrated in Figure 6. The dominant characteristic of this design is its extremely low mass. Initial designs did not at all resemble this design and, because of their large mass, collisions between bumper and mirror caused large impact forces at low frequencies that resulted in unacceptable vibrations of the scan mirror and its support structure.

Although most modes of vibration were well controlled by careful adherence to the above theories, one troublesome 1850 Hz mode emerged, late in the program, much larger than predicted. This was a result of a new brazing technique which had caused an unexpected tenfold decrease in mirror damping capacity. Because structural redesign of the mirror at that time would have entailed a severe schedule disruption, a hastier solution was sought. Therefore, a small device was designed, tested, and found to be extremely effective in damping out the vibrations of a much larger structure. This device, a damped vibration absorber, had only 4.5 percent of the mirror mass, but was still able to reduce mirror vibration from approximately ± 30 to ± 4 μ inches.

This simple device consisted of a viscoelastic material (an RTV) to provide damping and a steel mass to "work" the material; see Figure 9 for a cutaway view of the vibration absorber. The stiffness of the elastomer and the thickness of the bond line were important parameters in determining natural frequency of the absorber. Glass beads were used to control bondline thickness. Stiffness of the RTV was a controlled Shore 60A.

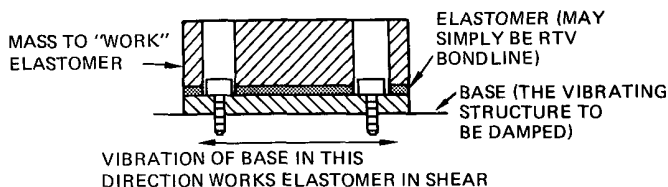


Figure 9. Damped vibration absorber

Simply stated, the application of this damped vibration absorber involves tuning the natural frequency of the device until it is roughly (to within ± 20 percent) equal to the frequency of the troublesome mode. Then, when the device is attached to the vibrating structure, vibration at this frequency will cause the device to "sing" at its own natural frequency, thereby working the elastomer and absorbing vibrational energy.

Such an absorber with a steel mass tuned to the resonating mode is generally much more effective in terms of weight than viscoelastic material alone, which is the more usual solution. (Merely bonding a sheet of elastomer to a surface without any mass to work the elastomer is a very inefficient method of providing damping.) Also, this absorber has the important advantage of being a simple screw-on device that is as readily adaptable to the latter as to the earlier stages of design (a "quick fix"). Because of the remarkable effectiveness and simplicity of this device, such vibration absorbers have since found successful applications in a number of other programs at Hughes Aircraft Company.

Energy losses

Energy was lost during turnaround in three ways, and it was critical that each loss be minimized. The first loss was energy dissipated by structural vibration. Secondly, energy was left in the bumper mass after turnaround because spring velocity was equal to mirror velocity at the completion of turnaround (since the spring and mirror had been in contact and had been moving together), and the velocity-spring mass product constituted a momentum that the spring absorbed during turnaround. This energy was therefore lost from the mirror. The third cause of energy loss was friction at the point of contact between the mirror and the spring.

Minimizing the first loss (due to structural vibration) was a function of frequencies and stiffnesses, as discussed before. Minimizing the second loss (momentum left in the spring mass) involved the following considerations:

- Using a pure spring having an absolute minimum mass as opposed to some massive bumper assembly on top of a spring
- Designing the leaf spring bumpers to operate at a safe but high stress level in order to store maximum energy in minimum spring mass
- Tapering the springs to distribute the stress more evenly over their length.

The third loss, to friction, was minimized by designing a contact surface having a particular radial shape (see Figure 10). The tip of the leaf spring tended to rotate as it was deflected, and this rotation constituted a sliding motion between the two contacting surfaces. Since the velocity of the contact point on the mirror is not perpendicular to the mirror surface, this velocity also has a component which constitutes a sliding motion. By selecting a particular radius, it is possible to make the two sliding velocities equal and thereby eliminate relative sliding. The purpose of this design was to minimize sliding and maximize rolling friction. Since rolling friction is less than sliding friction, it was expected that energy losses from friction would be reduced. It was also expected that structural vibrations excited by friction force frequencies would be reduced. The contacting surfaces consisted of a flat polished metal surface on the mirror and a Delrin AF (several other materials were also tested) radially shaped button bonded to the tip of the leaf spring.

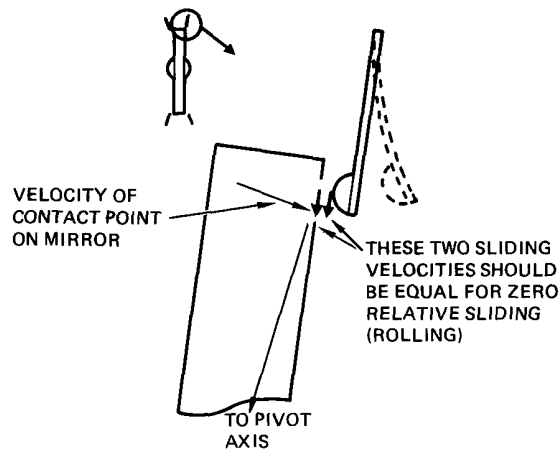


Figure 10. Rolling radius on leaf spring minimizes friction

To ensure proper operation of the scan mechanism, it is essential that bumper turnaround time be very nearly constant throughout mission life (33-percent duty cycle times two-year life or eight months of continuous operation). Hence any apparent softening of the spring with life, wear of the contacting surfaces, or creep of the polymeric stop will adversely affect performance. Therefore, an accelerated life test was conducted to demonstrate that the bumpers will perform within specified limits throughout the mission life and that the springs will not become subject to fatigue. The accelerated life test mechanism that was designed to simulate the oscillation of the scan mirror assembly consisted of two inertias mounted back to back. Since each inertia had associated with it four bumper assemblies, eight bumpers could be simultaneously tested for wear.

With eight bumpers, it was not only possible but also highly desirable to test various materials simultaneously. Several materials known for their excellent wear resistance were therefore selected for test. These were: teflon-filled delrin (Delrin AF), teflon-filled polyimide, teflon-filled lexan, teflon-filled nylon, MoS₂-filled polyimide, and teflon-filled aramid. All bumpers passed the accelerated test, which was conducted in a vacuum; Delrin AF showed the least wear.

After the conclusion of the accelerated life test, a nonaccelerated life test of a complete flight quality scan mirror assembly was conducted in a vacuum. The purpose of this test was to verify the integrity of this entire assembly over a full, nonaccelerated lifetime. Whereas the accelerated life test involved only the bumper assemblies, this nonaccelerated life test dealt with the entire scan mirror assembly, including the bumper assemblies, flexural pivots, electronics, and optical properties of the scan mirror. Minor changes were measured, but all parameters remained within the limits specified for one lifetime.

Conclusions

Two major mechanical problems were solved during this program.

- Structural vibration was reduced to a remarkably low level in view of the impact energies inherent in the mechanism (to less than 2 μ rad at 7 Hz, the primary mode of vibration occurring when pivots on the mirror deformed in shear)
- Mirror energy was conserved at each turnaround in order to ease the requirements for the torquer and control system, which provided energy only during the 0.010-second bumper impact time.

The first problem was solved by understanding the collision frequencies that occurred when the mirror mass impacted the bumper mass and then designing bumpers that had impact frequencies distinct from all natural frequencies of the system.

It is difficult to compare two complex systems simply on figures of merit, because of the many parameters involved, but compared with a previous-generation object-space scanning system, i.e., the very successful Multispectral Scanner, the Thematic Mapper scan mirror had 2.6 times the optical clear aperture, yet vibration was reduced significantly. The most troublesome mode was reduced almost two orders of magnitude.

The second problem was solved by using tapered leaf springs having very low mass and by making the contacting surface a rolling radius in order to maximize rolling and minimize sliding friction. The result was a high, 99-percent coefficient of restitution.

These very significant developments in scan mirror technology advanced the ability of large optical scanning systems to provide high resolution and high scan efficiency.

The spectacular imagery that this system has provided is typified by Figure 11, a scene of Washington, D.C., in which the reflecting pool and Lincoln Memorial are clearly visible as are the two wings of the capitol building, i.e., the House and the Senate. The exit ramps from interstate freeways are visible. Even the shadow from the Washington Monument can be seen!

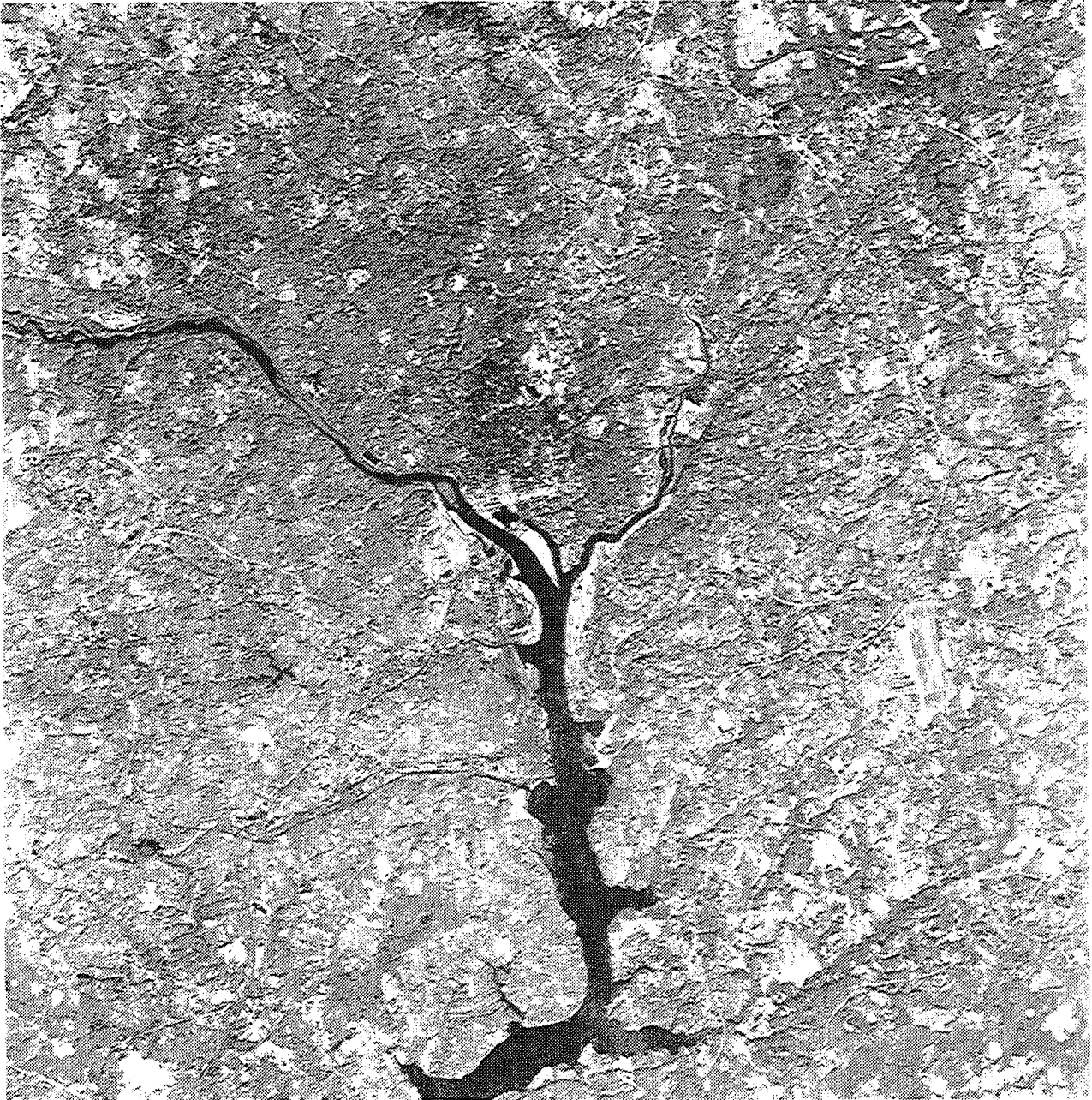


Figure 11. Thematic Mapper scene of Washington, D.C.