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Midcourse Space Experiment Satellite Flight Measurements of Contaminants on Quartz Crystal Microbalances

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The Midcourse Space Experiment (MSX) is a Ballistic Missile Defense Organization demonstration and validation satellite program that has both defense and civilian applications. MSX was launched on April 24, 1996, and has uv, visible, and infrared instruments including the Space Infrared Imaging Telescope (Spirit 3) cryogenic telescope. MSX had several contamination-measuring instruments to monitor pressure, gas species, water and particulate concentrations, and condensable gas species. A cryogenic quartz crystal microbalance (CQCM) and four temperature-controlled quartz crystal microbalances (TQCMs) were part of this suite of contamination-measuring instruments onboard the satellite. The CQCM was located internal to the Spirit 3 cryogenic telescope and was mounted adjacent to the primary mirror. The CQCM provided a real-time monitor of contaminant mass deposition on the primary mirror, which was cooled to the same temperature as the mirror, ~20 K. Thermogravimetric analyses on the CQCM provided insight into the amount and species of contaminants condensed at various stages of the mission. The four TQCMs were positioned strategically on the outside of the spacecraft and operated at approximately −50°C to monitor the silicone and organic contaminant flux deposition on external surfaces at specific locations. During the first week of flight operation, all TQCMs recorded deposition rates in the 10–20-ng/cm^2-day (1–2-Å/day) range. The measured deposition rates continuously decreased, and after 100 days into the mission the thickness deposition rates had fallen to values between 0 and 0.2 Å/day, depending on TQCM location.

Nomenclature

A = active quartz crystal microbalance (QCM) crystal surface area, 0.317 cm^2
F = quartz crystal oscillation frequency, Hz
m = mass, g
t = thickness, Å
ΔF = change in QCM frequency, Hz
Δm = condensed mass, g
ρ = density, g/cm^3

Introduction

THE Midcourse Space Experiment (MSX) satellite (Fig. 1) was launched on April 24, 1996, into a 903-km, 99.4-deg orbit. MSX is a Ballistic Missile Defense Organization (BMDO) demonstration/validation program that has both defense and civilian applications.[1–4] With telescopes and imagers operating in the ultraviolet through infrared wavelength ranges, the spacecraft was able to identify and track ballistic missiles during midcourse flight. The telescopes and imagers also obtained data on test targets and space background phenomena, monitored in-flight contamination, and were used to investigate the composition and dynamics of the Earth's atmosphere.

MSX stayed in its parked-mode orientation for much of the time. In this mode, the $-Y$ face of MSX is facing toward the sun for maximum power generation by the solar panels. The $+Z$ face is into ram, and the $-X$ face is always toward Earth. The $+X$ direction is always nearly perpendicular to the sun vector to minimize thermal loading on the Space Infrared Imaging Telescope (Spirit 3) cryogenic telescope. Generally, the spacecraft is in parked mode prior to spacecraft maneuvers for dedicated experiments that require other orientations.

The Spirit 3 (Fig. 2) is a major part of the MSX spacecraft and has sensor system components cooled to temperatures varying between 10 and 65 K. Contamination of the mirrors, windows, and detectors by condensed gases was of concern inasmuch as the operational lifetime in space was projected to be approximately 12 months. Real-time, in-space monitoring of contaminant mass deposition on the telescope primary mirror was provided through the use of a cryogenic quartz crystal microbalance (CQCM). The MSX CQCM was located adjacent to, and thermally coupled to, the cryogenically cooled primary mirror of the Spirit 3 telescope. It was used to monitor the deposition of contaminants on the interior optics and, with associated optical data, was used to determine the degradation in performance of the primary mirror. Performance of the infrared sensor optical surfaces can be impaired by deposition of contaminant films on critical surfaces by 1) changing the reflectance/transmittance and

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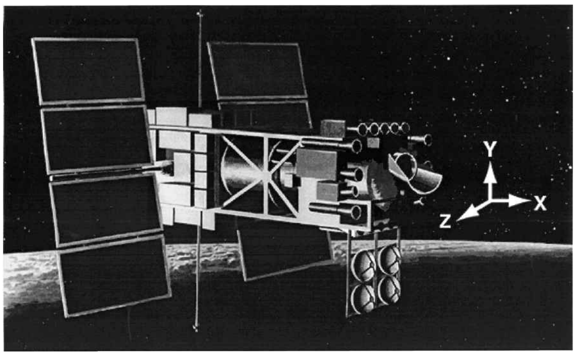

Fig. 1 Artist's drawing of MSX showing reference axis.

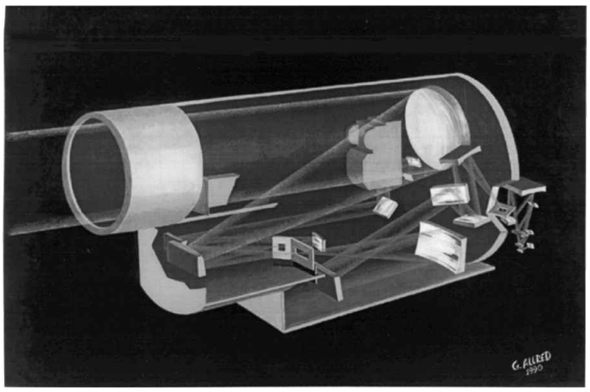

Fig. 2 Artist's drawing of Spirit 3 telescope sensor system.

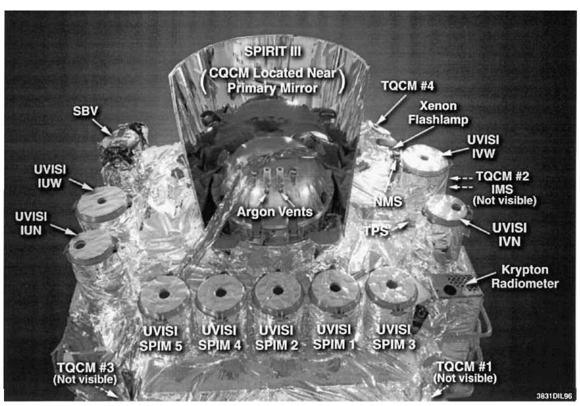

Fig. 3 Photograph of instrument section of MSX (+X direction).

2) increasing scatter of the optical element. In the infrared region, the effects of condensed films on sensor surfaces can be particularly detrimental due to selective wavelength absorption. The CQCM has been extremely useful for monitoring contaminant deposition during ground testing operations, preflight, and now, space.

The temperature-controlled quartz crystal microbalances (TQCMs) were located externally on the spacecraft at locations chosen to best characterize ambient contamination. As expected, the TQCMs having view factors of the solar panels have shown the largest deposition rates. TQCM 4, looking in the same general direction as the science instruments (+X), has also indicated measurable contaminant levels. Operating at approximately -50°C, the TQCMs are too warm for deposition of water vapor but are cold enough to condense organic and silicone contaminants. Therefore, they provide a convenient method for monitoring these contaminants. The locations of the science instruments are shown in Fig. 3, and the orientations of the various contamination-measuring instruments relative to the Spirit 3 and space-based visible (SBV) telescopes and the uv-visible (UVISI) instruments are indicated. The Spirit 3 sunshade and the argon-cooled cover are shown in the center of Fig. 3.

Effects of condensed gases on cold optics were previously investigated for the MSX program.[5,6] The primary mirror, shown in Fig. 2, is of most concern because it faces the entrance aperture through which most of the contaminants pass. By knowing the condensed mass determined by the CQCM, an estimate of the contaminant film thickness can be derived. Once the film thickness is known, the effect of the film on the mirror bidirectional reflectance distribution function (BRDF) and reflectance can be estimated from the laboratory measurements previously completed. Similarly, the effects of contaminants on the transmittance of optical elements can be deduced. The CQCM has been used to help identify the species of the contaminants condensed through thermogravimetric analysis (TGA) techniques. In the CQCM TGA mode, the sensing surface is allowed to warm up and the evaporated mass is measured as a function of crystal temperature. By monitoring the temperatures at which the various gases evaporate (which depend on their vapor pressure), the gas species can be identified and their approximate thickness determined.

Instrument Descriptions

CQCM

The CQCM is a Mark 16 model,[7] which was designed and fabricated by QCM Research of Laguna Beach, California. The CQCM (Fig. 4) uses two quartz crystals (to minimize temperature effects), which oscillate at 10 MHz and are positioned such that the sense crystal is exposed to the environment external to the sensor, whereas the reference crystal is protected from any deposition. The difference frequency is directly proportional to the mass condensed on the sense crystal. The mass sensitivity is proportional to $1/F^2$, where F is the oscillation frequency of the crystal. Because optical effects frequently are characterized using contaminant film thickness, it is more convenient to present the condensed mass data in terms of film thickness. To do this, the film density is required or, as is usually the case, a density of 1.0 g/cm^3 is assumed. The CQCM can detect condensed mass on the order of 10^{-9} g and was designed to operate at temperatures as low as 4 K. The quartz crystals were exposed to 100 krad (Si) from a cobalt-60 source at Johns Hopkins University, Applied Physics Laboratory (JHU/APL), to minimize radiation-induced frequency change during the time in orbit.

Two CQCMs were calibrated and characterized at temperatures as low as 10 K in a cryogenic calibration facility at the U.S. Air Force Arnold Engineering Development Center in Tullahoma, Tennessee.[8] After analyzing the test results, the unit with the best performance was chosen for installation in the Spirit 3 telescope. The CQCM was a valuable tool in monitoring the mirror status during cryogenic testing of Spirit 3 at the Utah State University Space Dynamics Laboratory, thermovacuum testing at the NASA Goddard Space Flight Center, and preflight measurements at the launch site.

The sensitivity of the CQCM to mass deposition (for 10-MHz crystals) is given by[7]

$$\Delta m/A = 4.42 \times 10^{-9} (\text{g/cm}^2 \cdot \text{Hz}) \Delta F\ (\text{Hz}) \tag{1}$$

The contaminant film thickness t can be calculated from

$$t(\text{cm}) = (\Delta m/A)/\rho$$
$$= 4.42 \times 10^{-9}\ (\text{g/cm}^2 \cdot \text{Hz}) \Delta F\ (\text{Hz})/\rho(\text{g/cm}^3) \tag{2}$$

The film density ρ was unknown but was assumed to be 1.0 g/cm^3 to facilitate film thickness calculations. The density range of spacecraft contaminant films has been measured to be between 0.8 and

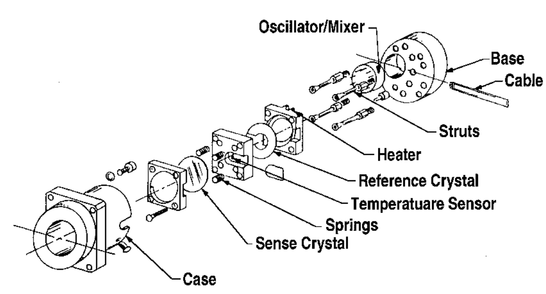

Fig. 4 Mark 16 CQCM assembly diagram.

1.5, depending on the species.[9] For unity density, the film thickness in angstrom is given by

$$t(\text{Å}) = 0.442\,(\text{Å/Hz})\Delta F\,(\text{Hz}) = 0.442 \tag{3}$$

for a frequency change of 1 Hz.

Similarly,

$$\Delta F\,(\text{Hz}) = 2.262 \tag{4}$$

for a film thickness of 1 Å.

TQCM

The TQCMs were Mark 10 units built by QCM Research. They were designed to operate at temperatures as low as −70°C and as high as 70°C. Preflight calibration and operational characteristics of six TQCMs were determined using ground test facilities at the Arnold Air Force Base.[10] From the performance data, the four best units were selected. The TQCM crystal temperatures were controlled by a built-in Peltier cooler/heater unit (see Fig. 5). As in the case of the CQCM, one of the two crystals was exposed to the environment while the other crystal was the reference crystal and was protected. The TQCM crystals operated at a frequency of 15 MHz, which made the TQCMs a factor of 2.25 times more sensitive than the CQCM. The mass sensitivity for the TQCMs is given by[11]

$$\Delta m/A = 1.96 \times 10^{-9}\,(\text{g/cm}^2 \cdot \text{Hz})\Delta F\,(\text{Hz}) \tag{5}$$

Using expressions similar to those derived for the CQCM results in the frequency-vs-thickness relationships (where again the density is assumed to be 1.0 g/cm^3),

$$t\,(\text{Å}) = 0.196\,(\text{Å/Hz})\Delta F\,(\text{Hz}) = 0.196 \tag{6}$$

for a frequency change of 1 Hz.

Similarly,

$$\Delta F\,(\text{Hz}) = 5.102 \tag{7}$$

for a film thickness of 1 Å.

The four TQCMs were mounted on the exterior of MSX with the direction cosines indicated in Table 1.

The satellite axes are indicated in Fig. 1. Thus, TQCM 1 is pointed with components in the $(-X, Y, Z)$ directions, TQCM 3 has $(Y, -Z)$ components, and TQCM 4 has $(X, -Y, Z)$ components. TQCM 2 points in the $+Z$ direction and, therefore, is looking primarily in the satellite ram direction. The TQCM covers limit their fields of view (FOV) to a right cone with approximately 64-deg half-angle. Both TQCMs 1 and 2 have view factors that contain considerable area of the solar panels. TQCM 3 was positioned to look in the wake direction, where minimal contamination levels were expected. TQCM 4 was mounted on the $+X$ face of the spacecraft and, thus, provided the deposition rate on the surfaces where all of the science instruments were located. The $+X$ face of the spacecraft was predicted to cool to temperatures on the order of −20°C. Therefore, the deposition levels measured by the TQCMs at −50°C represent a worst-case condition for the uv-visible instruments of UVISI and SBV.

Table 1 TQCM direction cosines

TQCM no.	X	Y	Z
1	−0.865	0.251	0.433
2	0	0	1.000
3	0	0.500	−0.865
4	0.896	−0.213	0.388

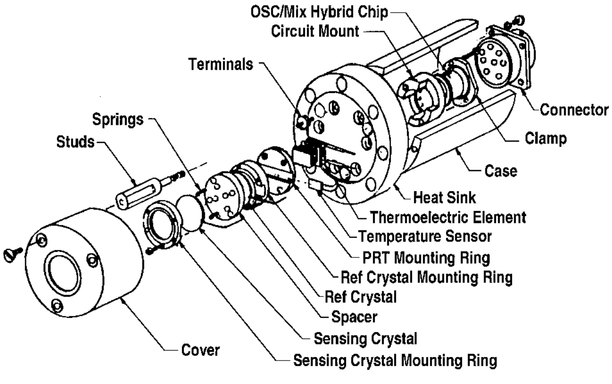

Fig. 5 Mark 10 TQCM assembly diagram.

The TQCMs were mounted on individual radiators, which were isolated from the main frame of the spacecraft to allow better thermal control. The heat from each Peltier thermoelectric device was radiated to space by the radiators. TQCMs 2–4 maintained an operating temperature of −50°C, whereas TQCM 1 operated at a slightly warmer temperature, −43°C, because it was mounted on a smaller radiator. As the satellite rotated on the solar panel axis to achieve a commanded attitude, the projected area of solar panel within their FOVs varied. In addition to the solar panel, TQCM 1 viewed some of the spacecraft electronics module, located near the $+Z$ solar panels in Fig. 1. Furthermore, thermal blanketing of a UVISI box intrudes into TQCM 1's FOV. The degree to which the TQCMs can receive line-of-sight outgassed molecules from these surfaces has been calculated from spacecraft drawings.[12] The planned TQCM operational temperature range of −40 to −50°C was colder than most of the external contamination sources and was cold enough to condense most of the silicones and hydrocarbon species that were outgassed from the MSX materials.

Flight Data Processing

The QCM data consisted of normal and diagnostic telemetry frames. Normal frames contained science data, whereas the diagnostic frames also contained instrument operational status information. The QCM telemetry output was 1 byte/s into the MSX spacecraft housekeeping data stream in all spacecraft modes. The housekeeping data were telemetered to the ground in any of three ways: real time at 16 kbps, tape recorded at 25 Mbps and downlinked, or tape recorded at 5 Mbps and downlinked. All three types of QCM satellite data were downlinked to the Mission Control Center at JHU/APL. During early operations, the Air Force Satellite Control Network was also used to collect MSX housekeeping data.

The 16-kbps and 25-Mbps data streams provided a normal frame of QCM data every 40 s and, when commanded, a diagnostic frame every 52 s. The 5-Mbps data provided a QCM normal data frame every 200 s and, when commanded, a diagnostic frame every 260 s. All three types of data were downlinked to the Mission Processing Center as so-called level 0 data. They were then processed and sent to the Contamination Experiment Data Processing Center as level 1 data, and finally, after further processing, sent to the Contamination Experiment Data Analysis Center (CEDAC) as level 2 data. During early operations (first week of flight and before Spirit 3 cover ejection), all of the data analysis by the principal investigators took place on location at the CEDAC.

Flight Data Uncertainty

The QCM mass calibration expressions were obtained from the vendor, QCM Research. These values of 4.42×10^{-9} (g/cm$^2 \cdot$ Hz) for the CQCM and 1.96×10^{-9} (g/cm$^2 \cdot$ Hz) are estimated to be accurate within ±5%, based on earlier experiments in which density values for condensed gases were obtained.[9] The CQCM frequencies are stable within ±1 Hz. The TQCM stability is strongly affected by incident solar flux and other thermal conditions. Based on the laboratory operation of the MSX TQCMs and similar units,[8,10] a stable thermal condition may still result in a TQCM frequency variability (noise level) as large as ∼4 Hz.

Results

MSX CQCM

The CQCM has played a major role in determining the contamination environment in space for the MSX Spirit 3 telescope. The contaminant mass deposition rate measured by the CQCM is assumed

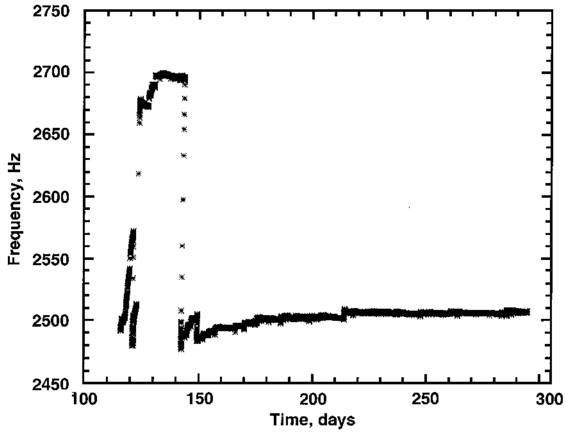

Fig. 6 CQCM frequency vs time in days (1996).

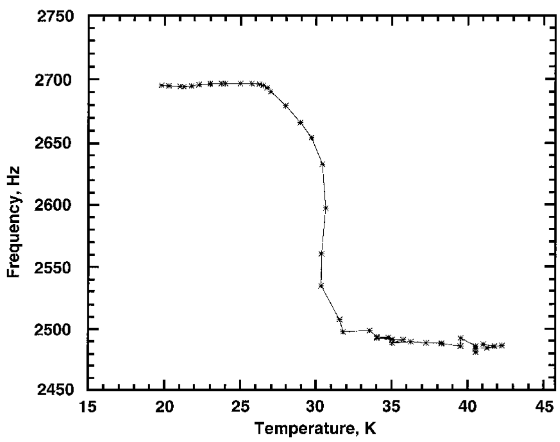

Fig. 7 Thermogravimetric analysis plot of CQCM with accreted mass.

to be the same as that on the primary mirror. By monitoring the deposited contaminant mass (or film thickness), a realistic estimate can be made of the health of the mirror.[13] The change in CQCM frequency with time is shown in Fig. 6 for the time period from launch (day 115, April 24, 1996) until day 294 (Oct. 20, 1996). The frequency-to-thickness conversion constant is 2.26 Hz/Å for an assumed film density of 1 g/cm^3. When launch occurred on day 115 (April 24), the CQCM frequency was approximately 2492 Hz, which was 12 Hz (~5 Å) higher than the frequency for the completely clean CQCM —2480 Hz. During the first 7 days after launch, there was a gradual buildup of contaminant film on the CQCM, even though the cryogenically cooled Spirit 3 protective cover was still in place. TGA of the CQCM contaminants provided a means for determining the species and amount of contaminant condensed.

From two TGAs performed prior to the cover release, it was determined that the contaminant deposited inside was primarily oxygen.[1] When the cover was released on day 122, there was an immediate rise in the CQCM frequency of about 163 Hz (72 Å). Another CQCM TGA was performed 19 days after the cover release to determine the mass and species of the 72-Å-thick film. The results of this TGA are shown in Fig. 7. Most of the condensate evaporated between 28 and 30 K and is believed to be argon, which came from the solid argon used as the cover coolant. This evaporation temperature is consistent with that seen from the argon vapor pressure-vs-temperature curve. The small deposit that evaporated between 30 and 32 K is believed to be oxygen, which was deposited prior to the cover release. The deposit evaporation curve determined by the TGA agreed well with the predicted evaporation rate characteristics of the two expected species, argon and oxygen; the model used for the predicted evaporation rates was based on the Langmuir equation and published vapor pressure data.

It is seen in Fig. 6 that very little film accumulation has occurred on the CQCM since the cover release. Most of the small incremental increases have occurred when the spacecraft was maneuvered into positions in which radiation from the Earth irradiated portions of the telescope baffles, causing them to heat up. This warming caused some of the previously adsorbed gases to be redistributed within the telescope. Since the last TGA was performed on day 149, there has been a CQCM frequency change of only 28 Hz (12 Å). As of Oct. 21, 1996, the total deposition on the CQCM since the telescope cooldown prior to launch was 154 Å. The TGAs have indicated that the condensed cryofilm on the primary mirror is composed of argon and oxygen, neither of which absorbs strongly in the infrared and, hence, which have minimal effect on mirror reflectance. Thin-film interference effects also are minimal due to the small film thickness. Even if it is assumed that the condensed species were either H_2O or CO (the infrared absorbing species most likely to be present), the change in mirror reflectance would be negligible. This is shown in Figs. 8 and 9, where the mirror reflectance is calculated assuming the 150 Å of condensed species to be all H_2O and all CO, respectively. The bare gold-coated mirror reflectance was assumed to be 0.98. Even at the peak of absorption for each specie, the reflectance has been reduced by an amount of less than 0.002 (0.2%).

Similarly, Figs. 10 and 11 show the effects of condensed argon and oxygen films, respectively, on the mirror scatter at a wavelength of 10.6 μm. In these figures, the data are for film thicknesses measured in micrometers, which are considerably greater than the 150-Å (0.015-μm) film on the primary mirror. The smallest thickness for each specie shown in Figs. 10 and 11 (~1.25 μm) indicates negligible scatter for these relatively thick films. As shown in Figs. 8–11, a film thickness of 150 Å had a negligible effect on both BRDF of the mirror and the mirror reflectance.

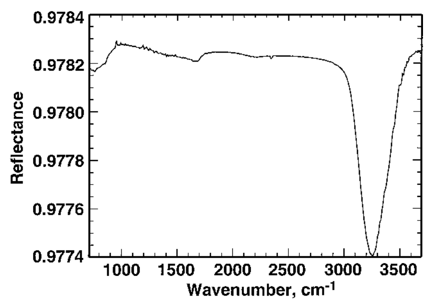

Fig. 8 Calculated effect of 150 Å film of H_2O on 20 K mirror reflectance.

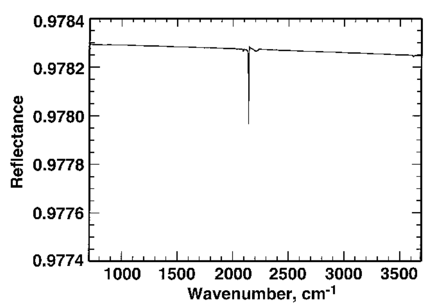

Fig. 9 Calculated effect of 150 Å film of CO on 20 K mirror reflectance.

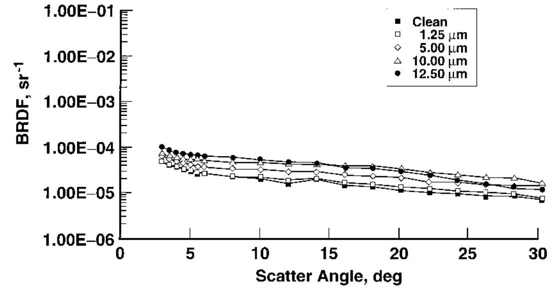

Fig. 10 Mirror scatter due to argon films condensed at 16 K and for 10.6-μm wavelength.

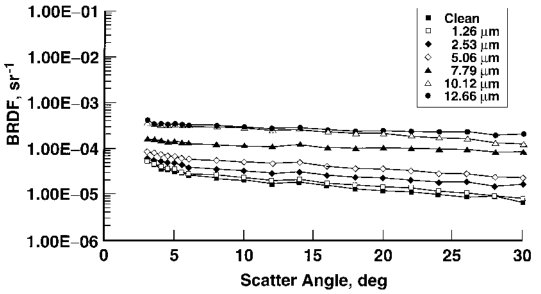

Fig. 11 Mirror scatter due to oxygen films condensed at 16 K and for 10.6-μm wavelength.

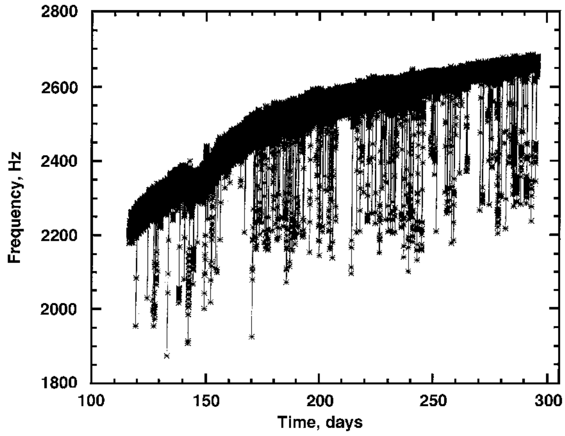

Fig. 12 TQCM 1 plot showing increase in frequency due to accreted mass at (+Y, +Z) location.

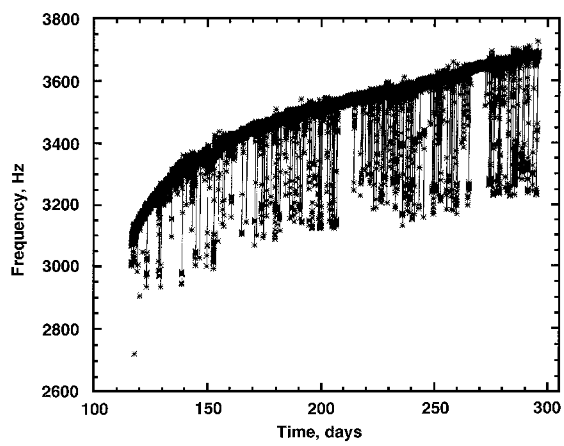

Fig. 13 TQCM 2 plot showing increase in frequency due to accreted mass at (+Z) location.

TQCMs

The frequency-vs-time plots are shown in Figs. 12–15, respectively, for TQCMs 1–4. The time covered is the same as that shown earlier for the CQCM. The TQCMs have the disadvantage of being sensitive to incident solar flux. Negative shifts in frequencies of 300–450 Hz have been seen for the TQCMs used on MSX for the situations of no sun or full sun. In the satellite-park mode, only TQCM 4 sees full sun (or near-full sun). The frequency of TQCM 4 (Fig. 15) changed by ~330 Hz between the times of full sun and out of sun. The ΔF due to solar flux on the QCM external crystals also was variable as the ΔF dropped from the 330 Hz seen in June to 240 Hz in October for TQCM 4. This decrease may be seasonal or it may be due to the spacecraft orbit precessing. TQCMs 1–3 also show similar solar effects in Figs. 7–9 but to a much lesser extent. Even though they do not view the sun directly in the spacecraft-park mode, they do see a solar effect that is due to reflected specular and scattered solar radiation from the solar panels and spacecraft blanketing and some thermal heat load from the surfaces in each TQCM's FOV.

Table 2 Film thickness deposition on each of the QCMs as of Oct. 21, 1996

QCM	Contaminant thickness, A	Location
TQCM 1	97	$+Y, +Z$
TQCM 2	121	$+Z$
TQCM 3	6	$+Y, -Z$
TQCM 4	42	$+X, +Z$
CQCM	154	Spirit 3 telescope

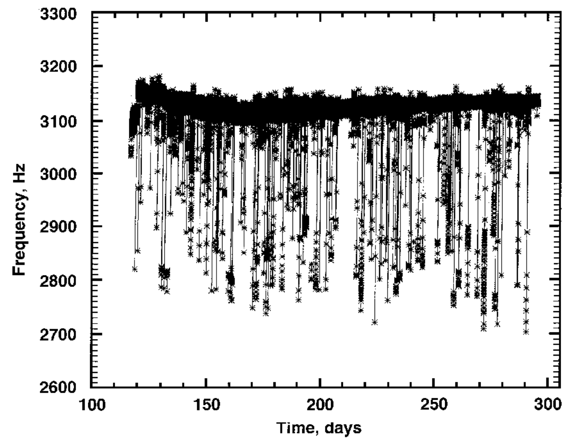

Fig. 14 TQCM 3 plot showing increase in frequency due to accreted mass at (+Y, $-Z$) location.

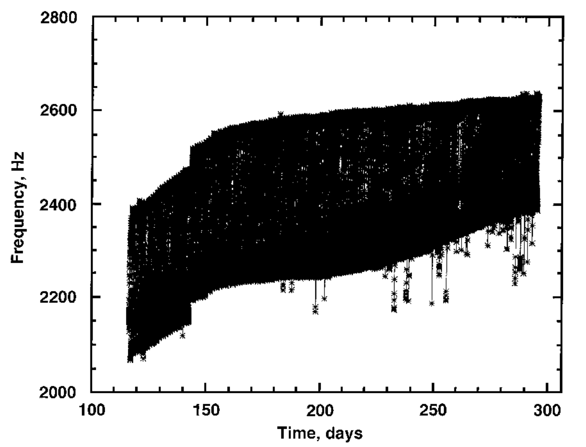

Fig. 15 TQCM 4 plot showing increase in frequency due to accreted mass at (+X) location.

The many spikes in the data of Figs. 12–15 are indicative of times when the spacecraft was maneuvered out of park mode in a manner that caused direct solar irradiance on the individual QCM that normally did not view the sun directly. This caused the TQCM frequency to drop 300–400 Hz, depending on the TQCM and whether it was exposed to full or partial sun. These solar effects complicate the data analysis on a short-term basis, but the data corresponding to TQCM darkness times can be used to determine the long-term deposition thickness and rates. Using the data points at the top of the curves, which correspond to the darkness times, a thickness plot for the condensate has been determined and is shown in Fig. 16. The thickness is plotted vs mission elapsed time (MET) in days. The total film thickness deposited for TQCMs 1–4 and the CQCM are shown in Table 2.

TQCMs 1 and 2 have the largest deposition rates of the four TQCMs, as seen in Fig. 16. They both have view factors of the solar panels that apparently are the major sources of contaminants on MSX. The rate of deposition has slowed, but the deposition rate on these two TQCMs is still appreciable, on the order of 0.2 Å/day. TQCM 3, as expected, has shown the smallest amount of deposition. TQCM 4, looking in the same general direction as the science instruments, $+X$, has indicated a total deposition of 42 Å as of Oct. 21, 1996. It, too, is still picking up mass but at a much reduced rate.

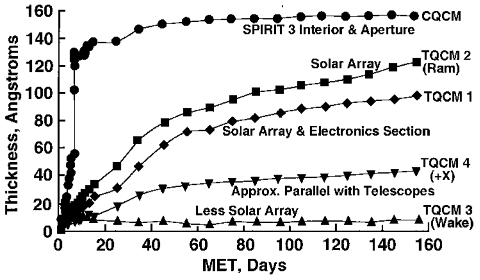

Fig. 16 Accreted contaminant film thickness vs MET for CQCM and four TQCMs.

Summary and Conclusions

The MSX satellite QCMs have proven to be quite useful for monitoring the on-orbit contaminant mass buildup on the Spirit 3 cryogenic telescope primary mirror and on the satellite external surfaces. After 168 days in orbit (Oct. 21, 1996), the CQCM (and primary mirror) have accumulated 154 Å of condensate on the 20 surfaces. Most of this condensate was due to the argon condensed during the Spirit 3 cover release. Essentially all of the condensate has been argon, oxygen, and nitrogen with less than 1% water and carbon dioxide as determined by the thermogravimetric analyses before and after the cover release. Data on the optical effects of condensed films on cryogenic mirrors at 20 K obtained in preflight ground tests indicate that a 154-Å-thick film of any condensed gas will have negligible effects on the mirror scatter and reflectance at this temperature.

The four TQCMs mounted on satellite external surfaces have been operated at temperatures of approximately −50°C and have shown accumulations between 6 and 121 Å, depending on the TQCM location on the spacecraft. The TQCMs having the solar panels in their FOV have shown the largest deposition rates. The solar radiation incident on the crystals caused two separate effects: 1) a quick response negative shift in output frequency of 300–400 Hz when solar radiation was incident on the sensing crystal and 2) the solar uv polymerization of the contaminant such that during TGAs only a small portion of the condensed mass was evaporated.

The TQCMs are continuing to accumulate mass, and the long-term trends established for MSX will be extremely valuable for future BMDO satellites.

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References

[1] Wood, B. E., Hall, D. F., Lesho, J. C., Dyer, J. S., Uy, O. M., and Bertrand, W. T., "Quartz Crystal Microbalance (QCM) Flight Measurements of Contamination on the MSX Satellite," *Optical System Contamination V and Stray Light and System Optimization, SPIE Proceedings*, edited by A. P. M. Glassford, R. P. Breault, and S. M. Pompea, Vol. 2864, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1996, pp. 187–194.

[2] Mill, J. D., O'Neil, R. R., Price, S., Romick, G. J., Uy, O. M., Gaposchkin, E. M., Light, G. C., Moore, W. W., Jr., Murdock, T. L., and Stair, A. T., Jr., "Midcourse Space Experiment: Introduction to the Spacecraft, Instruments, and Scientific Objectives," *Journal of Spacecraft and Rockets*, Vol. 31, No. 5, 1994, pp. 900–907.

[3] Huebschman, R. K., and Pardoe, H. T., "The Midcourse Space Experiment Spacecraft," AIAA Paper 92-0977, Feb. 1992.

[4] Uy, O. M., Benson, R. C., Erlandson, R. E., Boies, M. T., Lesho, J. C., Galica, G. E., Green, B. D., Wood, B. E., and Hall, D. F., "Contamination Experiments in the Midcourse Space Experiment," AIAA Paper 96-0219, Jan. 1996.

[5] Seiber, B. L., Bryson, R. J., and Wood, B. E., "Cryogenic BRDF Measurements at 10.6 μm on Contaminated Mirrors for MSX Satellite Program," *Optical System Contamination: Effects, Measurements, and Control IV, SPIE Proceedings*, edited by A. P. M. Glassford, Vol. 2261, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1994, pp. 170–180.

[6] Wood, B. E., and Roux, J. A., "Infrared Optical Properties of Thin H_2O, NH_3, and CO_2 Cryofilms," *Journal of the Optical Society of America*, Vol. 72, No. 6, 1982, pp. 720–728.

[7] Wallace, D. A., and Wallace, S. A., "QCM Research Operating Manual—Mark 16," QCM Research, Laguna Beach, CA, Jan. 1996.

[8] Bryson, R. J., Bailey, A. B., Seiber, B. L., Bertrand, W. T., Jones, J. H., and Wood, B. E., "Cryogenic Quartz Crystal Microbalance: Characterization and Calibration for Midcourse Space Experiment," *Optical System Contamination: Effects, Measurement, and Control III, SPIE Proceedings*, edited by A. P. M. Glassford, Vol. 1754, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1992, pp. 205–214.

[9] Seiber, B. L., Bryson, R. J., Young, R. P., Sr., Wood, B. E., and Dykeman, D., "Effects of Cryocontaminants on Cryogenic Superpolished Mirror and Superpolished Quartz Crystal Microbalance," *Optical System Contamination: Effects, Measurement, and Control III, SPIE Proceedings*, edited by A. P. M. Glassford, Vol. 1754, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1992, pp. 215–225.

[10] Bryson, R. J., Seiber, B. L., Bertrand, W. T., Jones, J. H., and Wood, B. E., "MSX Thermoelectric Quartz Crystal Microbalances—Calibration and Characterization," *Optical System Contamination: Effects, Measurements, and Control IV, SPIE Proceedings*, edited by A. P. M. Glassford, Vol. 2261, Society of Photo-Optical Instrumentation Engineers, Bellingham, WA, 1994, pp. 256–268.

[11] Wallace, D. A., and Wallace, S. A., "QCM Research Operating Manual—Mark 10," QCM Research, Laguna Beach, CA, Jan. 1996.

[12] Silver, D. M., "Midcourse Space Experiment Molecular Contamination Modeling Predictions for the Early Orbital Operations," Applied Physics Lab., Rept. RCO-96-106, Johns Hopkins Univ., Laurel, MD, April 1996.

[13] Wood, B. E., Seiber, B. L., Bertrand, W. T., and Uy, O. M., "Effects of Thin Cryo-Contaminant Films on Midcourse Space Experiment (MSX) Satellite Cryo-Optics," AIAA Paper 96-0221, Jan. 1996.

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