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HVRM: A SECOND GENERATION ACE-FTS INSTRUMENT CONCEPT

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I. INTRODUCTION

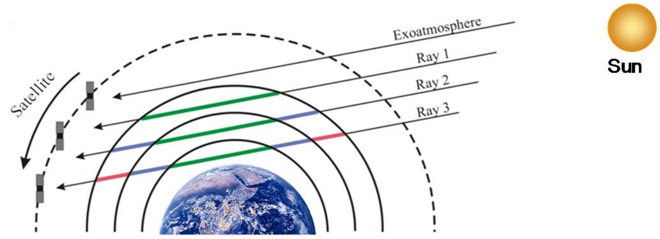
The Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) is the main instrument on-board the SCISAT-1 satellite, a mission mainly supported by the Canadian Space Agency [1]. It is in Low-Earth Orbit at an altitude of 650 km with an inclination of 74E. Its data has been used to track the vertical profile of more than 30 atmospheric species in the high troposphere and in the stratosphere with the main goal of providing crucial information for the comprehension of chemical and physical processes controlling the ozone life cycle. These atmospheric species are detected using high-resolution (0.02 cm^{-1}) spectra in the 750-4400 cm^{-1} spectral region. This leads to more than 170 000 spectral channels being acquired in the IR every two seconds. It also measures aerosols and clouds to reduce the uncertainty in their effects on the global energy balance. It is currently the only instrument providing such in-orbit high resolution measurements of the atmospheric chemistry and is often used by international scientists as a unique data set for climate understanding.

The satellite is in operation since 2003, exceeding its initially planned lifetime of 2 years by more than a factor of 5. Given its success, its usefulness and the uniqueness of the data it provides, the Canadian Space Agency has founded the development of technologies enabling the second generation of ACE-FTS instruments through the High Vertical Resolution Measurement (HVRM) project but is still waiting for the funding for a mission.

This project addresses three major improvements over the ACE-FTS. The first one aims at improving the vertical instantaneous field-of-view (iFoV) from 4.0 km to 1.5 km without affecting the SNR and temporal precision. The second aims at providing precise knowledge on the tangent height of the limb observation from an external method instead of that used in SCISAT-1 where the altitude is typically inferred from the monotonic CO_2 concentration seen in the spectra. The last item pertains to reaching lower altitude down to 5 km for the retrieved gas species, an altitude at which the spectra are very crowded in terms of absorption. These objectives are attained through a series of modification in the optical train such as the inclusion of a field converter and a series of dedicated real-time and post-acquisition algorithms processing the Sun images as it hides behind the Earth. This paper presents the concepts, the prototypes that were made, their tests and the results obtained in this Technology Readiness Level (TRL) improvement project.

II. ACE-FTS PRINCIPLE

The ACE-FTS instrument measures the atmospheric transmittance through sun occultation during sunrises and sunsets. The principle during a sunset is illustrated in Fig. 1. The instrument is directly looking at the Sun and takes a series of measurement from the exoatmosphere until the sun disappears behind the horizon or is hidden by the cloud cover. This results in an atmospheric profile ranging from 120 km, limited by the instrument sensitivity, to approximately 5 km or higher depending on the cloud cover. The exoatmosphere measurement is the reference and the transmission corresponding to a given altitude in the atmosphere is found by doing the ratio of the measurement and the exoatmosphere spectrum. The measurements contains the atmospheric transmission at multiple tangent heights so the series of measurements needs to be combined and inverted to retrieve the atmospheric vertical profile.



$$\text{Transmittance}_i = \frac{\text{Signal}_i}{\text{Signal}_{exo}}$$

Fig. 1: Solar occultation measurement concept. The measured transmittance is the ratio of the Sun signal acquired above the atmosphere – in the exoatmosphere – and the signal acquired at time *i*.

This is done at the sunsets and sunrises. The number of measurements taken and the altitude difference between each measurement varies during the year. It depends on the angle between the satellite orbit and the Earth-Sun vector, this angle is referred to as the beta angle. There is two periods of three weeks in June and December during which this angle does not allow the Sun to set and no measurements are possible. Measurements are taken every 2 seconds which results in a sampling of 6 km for a zero beta angle and of 2 km for a 55° beta angle. The spatial resolution at the tangent height is 4 km and is set by the instrument iFoV.

The atmospheric spectrum is acquired using a two-pass Fourier Transform Spectrometer. The optical layout of ACE-FTS is shown in Fig. 2. The interferometer is located after the sun-tracker and an optical relay that reduces the pupil size and reimages the pupil in the corner cube. The interferometer has mirrors that transform the single pass into a double pass in the interferometer. This is combined with a synchronized opposite scan direction for the two corner cubes to reach an induced optical path difference between the two arms of eight times the corner cubes displacement leading to a very compact interferometer.

A dichroic located at the center of the primary mirror transmit the SWIR and reflects the VISNIR wavelengths. The transmitted light goes to a quad cell that tracks the Sun radiometric center and feeds its measurement back to the tracking mirror. The data acquisition is turned off when the sun flux gets below a threshold value to avoid low SNR measurements that would result in significant pointing errors. This threshold approach makes the system sensitive to the presence of clouds in the lower troposphere and can limit the lower altitude achievable in their presence.

The reflected light is imaged on two science detectors with 256 px x 256 px; one with a filter at 0.525 µm and the other at 1.02 µm [2]. Aerosols and clouds are monitored using the atmospheric extinction profiles derived from these imagers and provides important information on the flux variation over the solar disk.

The light modulated by the interferometer is imaged on two photo-voltaic detectors: an InSb detector for the higher wavenumbers and an MCT detector for the lower ones.

III. HVRM PROPOSED IMPROVEMENTS

Three improvements for a second generation ACE-FTS like instrument were proposed and investigated in the HVRM Space Technology Development Program (STDP). It has first been proposed to increase the vertical resolution of the measurements from 4.0 km to 1.5 km without affecting the SNR by using a horizontally elongated rectangular FoV instead of a square one. Second, the interpretation of the results obtained with ACE-FTS necessitates an accurate knowledge of the observed tangent height and of the pressure/temperature (pT) vertical profiles. These parameters are typically derived by analyzing CO_2 lines and assuming a weak variation of its concentration for a set of parameters. This typically yields an accuracy of approximately 1 km on the altitude knowledge. This approach also prevents the monitoring of the CO_2 altitude profile itself since it is used as the reference. While alternative tracers can be used to accomplish the latter [3], it is desirable to have a method independent of the atmospheric molecules. In HVRM, such a method based on the sun geometric image was investigated and is expected to have a tracking accuracy better than 100 m. Finally, the last improvement aims at lowering the altitude limit at which the measurements can be taken in the presence of clouds.

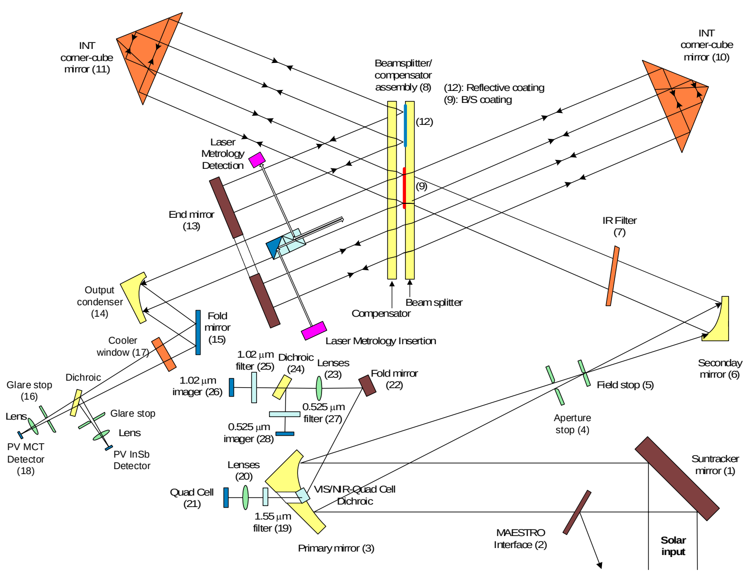


Fig. 2: ACE-FTS optical layout

A. Vertical resolution

The first proposed improvement is to increase the vertical resolution of the measurement without affecting the system throughput. This is done by replacing the optical relay following the tracking mirror by a more complex optical system that includes a field converter assembly that remaps the square instrument iFoV in a rectangular iFoV (decreased vertical and an increased horizontal iFoV) when projected on the Sun. The HVRM iFoV is compared to ACE in the left panel of Fig. 3 along with their relative aperture dimension. The field converter assembly is similar to the image splitter assemblies used in astronomy for integral field spectrographs except that it is used in the opposite direction i.e it remaps a linear iFoV into a square one. The HVRM field converter assembly divides the rectangular iFoV in three slices that are then remapped to form a square iFoV.

The HVRM modified input optical layout is shown in the right panel of Fig. 3. The field converter uses three mirrors to remap the field of view. This approach proved to be less sensitive to component positioning errors than the two mirror approach.

The optical tolerance budget has been allocated to the optical components to ensure that the iFoV has a full-width at half maximum below 1.5 km in the vertical direction and that the differential boresight error between the different segments is less than 60 m.

A structural-thermal-optical performance analysis was also conducted to evaluate the boresight error induced by solar heating during an image sequence acquisition. This was found to induce an absolute vertical pointing error of less than 80 m at the tangent height and a maximum variation lower than 15 m between the sunrise and the sunset. The differential boresight error between each FoV slice is expected to be significantly lower than this value, the thermal deformations being expected to induce a pointing error going in the same direction for all slices.

The field converter and the output optical relay were assembled in a flight-like breadboard to test this new optical assembly and increase its maturity level. The test main goals were to confirm that the FoV is not affected by launch like vibrations and that it is stable in temperature.

The three diamond turned mirrors made of aluminum 6061-T6 are shown in the top left panel of Fig. 4. No coatings are applied to yield bare aluminum surfaces and the irregularity requirement is set to 2 waves P-V at 632.8 nm. The two field mirrors have a radius of curvature of 132.3 ± 1.0 mm and the pupil mirror has one of 100.0 ± 1.0 mm. The mirror slices center of curvature are positioned within ± 50 µm one from another.

The field converter mirrors are assembled with the output optical relay in the breadboard shown in the bottom left panel of Fig. 4. Images of the input FoV seen through the system and of the FoV transformed into a square FoV after the field converter assembly are shown in the right panels of Fig. 4. The discontinuities in the FoV are found to have a negligible impact on the spectrometer ILS. The calculated ILS for a top hat ideal intensity distribution at 4400 cm^{-1} is 0.0339 cm^{-1} while the measured intensity distribution results in a 0.0341 cm^{-1} ILS.

Finite element analyses were conducted to confirm that the system would keep its alignment under launch vibration conditions and after thermal cycling. These were then confirmed by tests. The vibration profiles are extracted from GEVS GSFC-STD-7000A. Examples of results from the FEA analysis are shown in Fig. 5. The main result seen in this figure is that the measured excited frequencies match well the ones predicted by the FEA analysis.

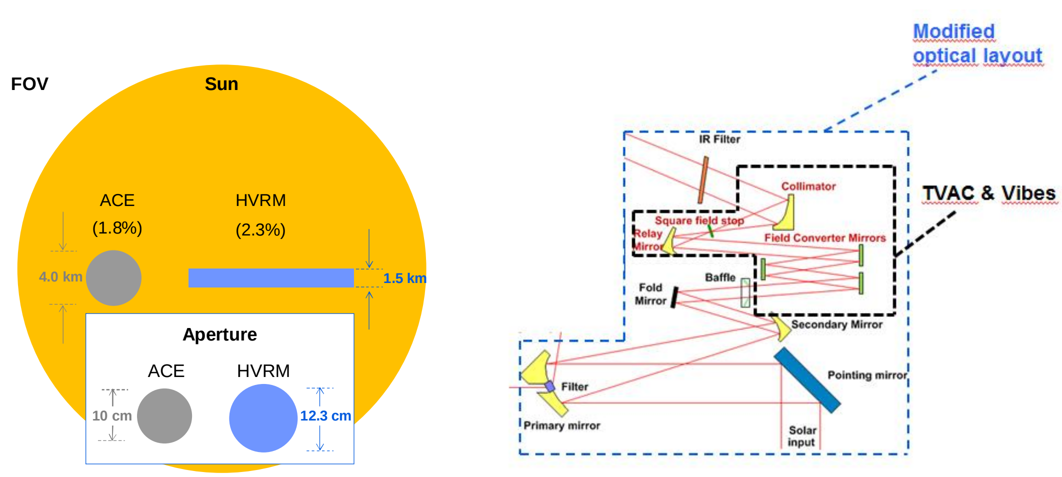


Fig. 3: A field of view and entrance pupil diameter comparison between ACE-FTS and HVRM projected on a representation of the sun is shown in the left panel. The new entrance optical layout used in HVRM to remap the FoV is shown in the right panel

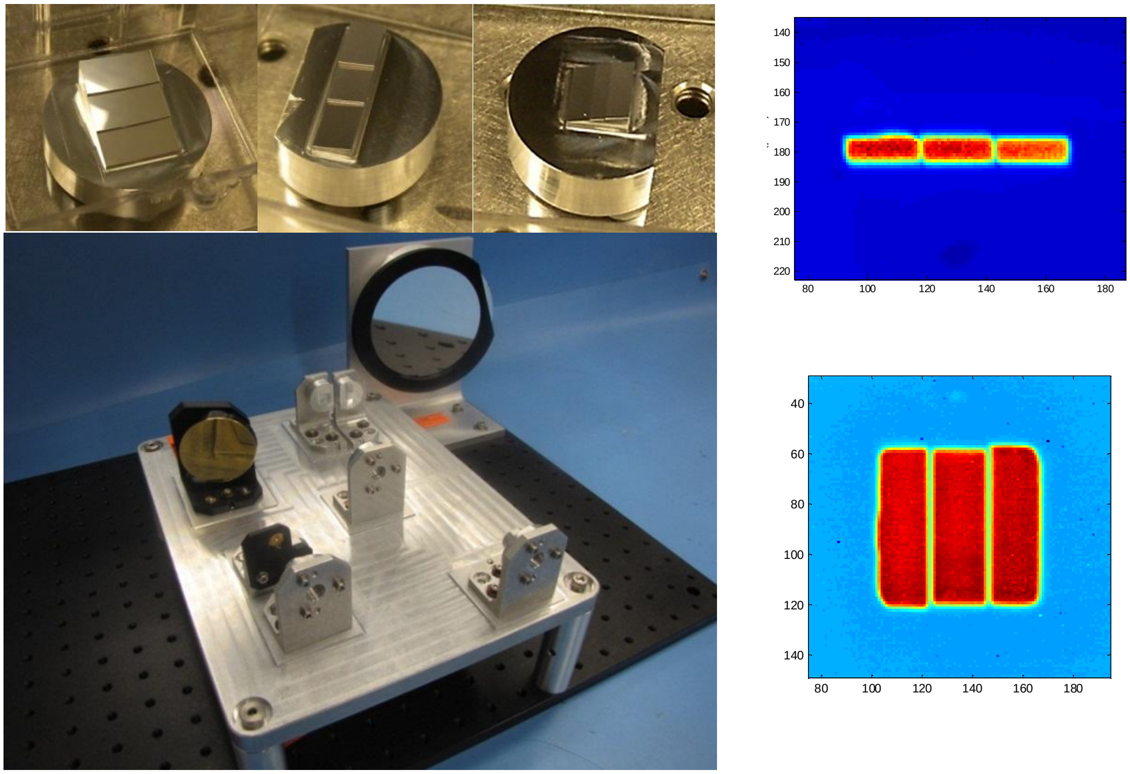


Fig. 4: Breadboard components and result images. The first field mirror, the pupil mirror and the second field mirror of the field splitter assembly are shown in the top left panel from left to right. The assembled breadboard is shown in the bottom left panel. The top right panel shows the image of a square field stop at the located at the system output as seen from the object plane. The bottom right panel shows the remapped rectangular FoV at the system output.

Following the vibration test, the breadboard was visually inspected to detect failures, inspected at the CMM to verify that the components alignment was unchanged and the FoV was measured before and after the vibration tests to confirm that it remained unchanged. All these tests were passed successfully with a FoV variation below the measurement accuracy of 0.4%.

The thermal cycling consisted in a first cold plateau at -45°C for 3.5h, a high temperature plateau of 40°C for 12.5h, a second low plateau at -45°C for 3.2h and a final warm plateau of 40°C for 5.4h. It was verified during those test that the FoV remained unchanged and that the boresight difference between each FoV slice did not vary. The FoV full-width at half maximum was found to vary by less than 0.4% which is the limit of the test sensitivity. No pointing error between each segment could be detected.

B. Altitude Knowledge

ACE-FTS currently estimates a tangent altitude by using CO_2 lines to determine the pressure and temperature in the observed FoV. The retrieved gas profiles are then function of this altitude that is estimated to be precise to ±500m. The second proposed improvement is to use geometric images of the sun to determine the tangent altitude and to increase the precision to a goal of ±50m and a threshold of ±100m.

A time series of Sun images taken with the ACE-FTS imager as it rises is shown in **Fig. *6***. It rises with an angle of 45° relative to an Earth horizon located towards the top left corner of the images. The part of the Sun being transmitted through the lower atmosphere is more refracted than the part going through the higher atmosphere with the consequence of flattening its image at lower altitudes. The refraction difference between the top and the bottom of the solar disk decreases as the Sun gets higher in the atmosphere leading to less flattening. The solar disk flattening or the solar extent defined as the ratio of the solar disk diameter perpendicular to the horizon over its diameter parallel to it can be computed from the time series of images. Different methods can be used to extract the effective atmospheric refractive index at the observed tangent height from a time series of solar extent measurements. The pT profiles and the observed tangent height are then computed from these measurements.

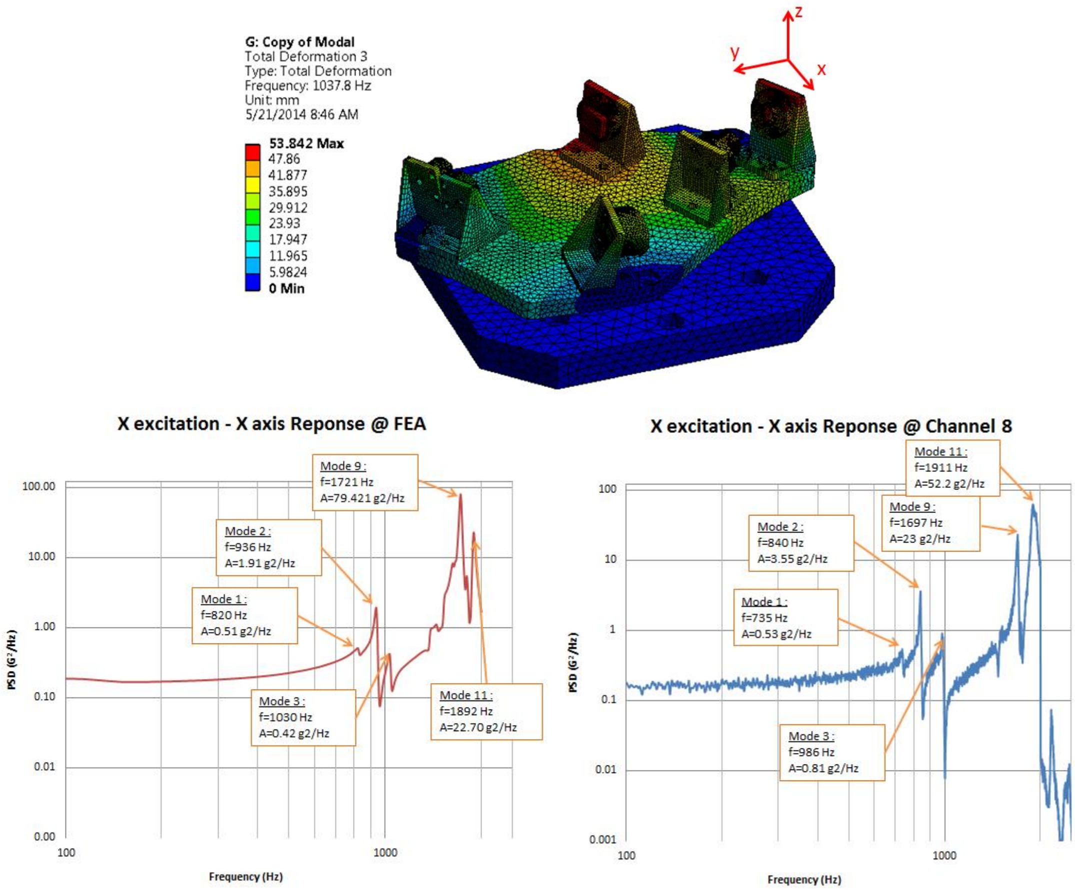


Fig. 5: Example of FEA analysis conducted in the HVRM project. The top panel shows an exaggerated view of the vibration mode 3. Resonant frequencies predicted by the FEA model (bottom left panel) are compared to the measured ones (bottom right panel) for the X axis. Channel 8 corresponds to the accelerometer measuring the x-axis response.

Since the tangent height is computed from the solar extent, any noise or error in the solar extent computation directly leads to an error on the tangent height estimate. Our preferred approach for the solar extent computation is to apply an algorithm to detect the Sun edge and to compute the solar extent from it. An example of computed solar extent and tangent heights are shown in Fig. 6. The remaining noise in this example led to a standard deviation on the computed tangent height of 106 m. We expect this value to be improved in a second generation ACE-FTS by using an imaging detector with more pixels that will resolve the solar edge with more precision.

C. Lower altitude in cloudy conditions

The Sun tracking system is using a quad cell that follows its radiometric center. The system stops to track the Sun when the flux on the quad cell gets below a pre-determined threshold value to avoid low SNR measurements and significant tracking errors.

A first observation that was made when analyzing the ACE-FTS tracking data is that the threshold seems to be significantly too conservative. As a consequence, the tracking cuts-off at higher altitude then what could achieved. The presence of clouds in the lower atmosphere can also significantly attenuate the Sun intensity reaching the quad cell and bring it below the threshold value resulting in the tracking stopping at altitudes higher than the cloud cover.

To improve this, it is proposed to use Sun images to track the Sun instead of a quad cell and to better determine the threshold cut-off value. The Sun images can be analyzed to filter out cloudy regions and continue the tracking. This work still remains to be implemented and tested at the moment of writing this paper.

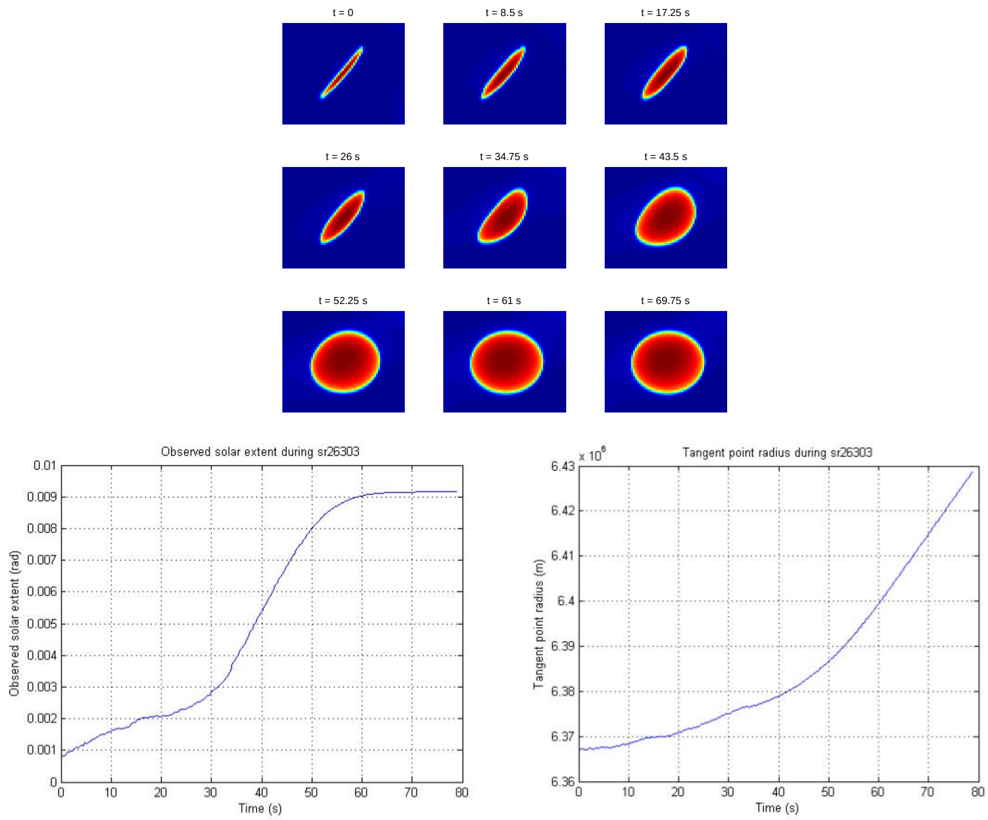


Fig. 6: Tangent height computation from solar extent. Nine image samples of a time series taken during a sunrise with ACE-FTS are shown in the top panel. The solar extent computed for this time series is given in the bottom left panel and the computed tangent height is shown in the bottom right panel.

IV. SUMMARY

The work accomplished to improve the performances of a second generation ACE-TS instrument has been presented. A rectangular FoV is remapped into a square using a field converter assembly to improve the vertical spatial resolution without affecting the throughput. The new optical system was assembled in a flight-like breadboard and successfully passed vibration and thermal cycling tests. A new method to compute the tangent height based on geometric images of the Sun was implemented and yielded an accuracy of 106 m on ACE-FTS images. This is expected to be significantly better on a second generation mission in which the imager would have a better spatial resolution. Finally, the same geometric images are proposed to be used to detect clouds and to adjust the tracking algorithm accordingly to prevent data acquisition cut-offs at higher altitudes than 5 km.

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