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## HIGS-INSTRUMENT: DESIGN AND DEMONSTRATION OF A HIGH PERFORMANCE GAS CONCENTRATION IMAGER

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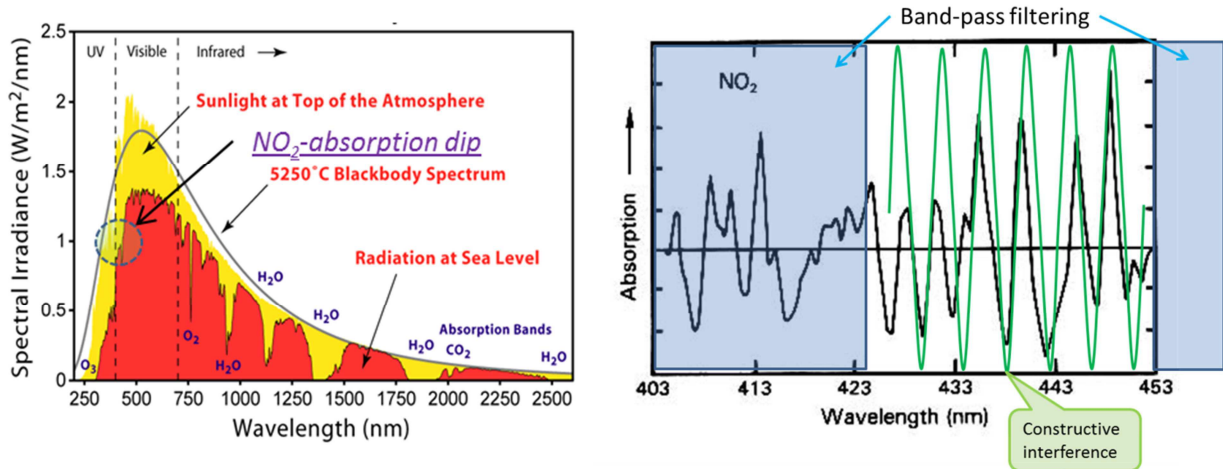
### ABSTRACT

Climate change and environmental conditions are high on the political agenda of international governments. Laws and regulations are being setup all around the world to improve the air quality and to reduce the impact. The growth of a number of trace gasses, including CO<sub>2</sub>, Methane and NO<sub>x</sub> are especially interesting due to their environmental impact. The regulations made are being based on both models and measurements of the trend of those trace gases over the years. Now the regulations are in place also enforcement and therewith measurements become more and more important. Instruments enabling high spectral and spatial resolution as well as high accurate measurements of trace gases are required to deliver the necessary inputs. Nowadays those measurements are usually performed by space based spectrometers. The requirement for high spectral resolution and measurement accuracy significantly increases the size of the instruments. As a result the instrument and satellite becomes very expensive to develop and to launch. Specialized instruments with a small volume and the required performance will offer significant advantages in both cost and performance. Huib's Innovative Gas Sensor (HIGS, named after its inventor Huib Visser), currently being developed at TNO is an instrument that achieves exactly that. Designed to measure only a single gas concentration, opposed to deriving it from a spectrum, it achieves high performance within a small design volume. The instrument enables instantaneous imaging of the gas distribution of the selected gas. An instrument demonstrator has been developed for NO<sub>2</sub> detection. Laboratory measurements proved the measurement technique to be successful. An on-sky measurement campaign is in preparation. This paper addresses both the instrument design as well as the demonstrated performances.

### I. INTRODUCTION AND MEASUREMENT PRINCIPLES

Currently the NO<sub>2</sub> distribution in the Earth's atmosphere is retrieved from the spectra obtained using large dispersive (grating based) spectrometer instruments like SCHIAMACHY, GOME and OMI. Integration times of about 1s are required to arrive at a sufficient Signal to Noise Ratio (SNR) where the effective ground pixel on Earth is about 7km in flight direction. Most often some binning in the swath direction is used leading to square ground pixels of e.g. 7 x 7km in Nadir direction. The drawback of a spectrometer is that the intensity being measured is dispersed over many pixels resulting in low signal levels per pixel. Scientists are asking for smaller ground pixels (2 x 2km or smaller) while preserving sufficient SNR values (Overall 20% measurement accuracy is required for NO<sub>2</sub> [1]). This is virtually impossible since the scattering by the Earth is a constant, as is the output of the Sun, so the only way for these type of instruments to decrease the ground pixel size is by moving towards larger entrance apertures and smaller f-numbers in the optical design. This leads to larger, heavier, and more expensive instruments. Alternative approaches like Fourier Transform Spectrometers (FTS) or filter based instruments often encounter other types of errors that limit the instrument performance too much. As FTS instruments [2, 3] properties vary within a measurement, the variation of the ground scene and co-registration issues limit their performance. Filter based instruments [4] often have limited sensitivity or cannot distinguish well between gasses.

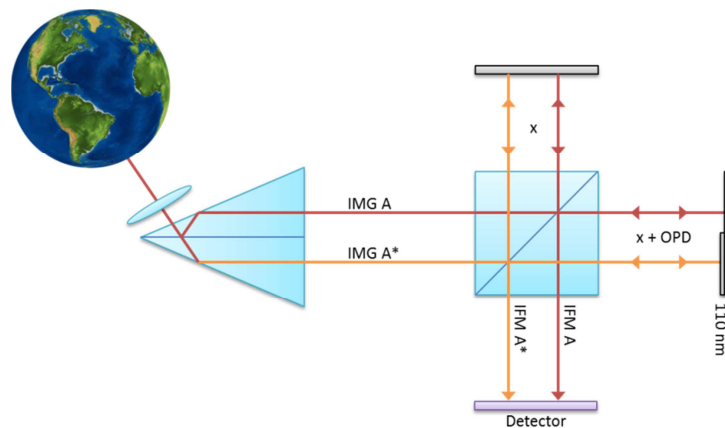
The HIGS instrument is a newly developed measurement concept that combined the useful properties of these instrument types, where it minimizes the conventional issues. Core of the measurement principle is the interferometric creation of a filter that closely matches the target gas spectral lines within a band. As a result the system is highly sensitive for this gas alone and requires significantly less correction for other gasses, see Fig. 1.



**Fig. 1.** Left: Earth spectral irradiance plot example (courtesy Wikipedia), showing gas absorption bands and spectrum complexity. Right: Schematic illustration of the HIGS spectral filtering principle

Sunlight reflected from Earth has a complex spectrum containing Solar emission, the Earth albedo and absorption features of gases in the atmosphere. See Fig. 1. For NO<sub>2</sub> measurement often an absorption band around 440nm is used, as this band is least affected by other gas absorptions and has a reasonable absorption depth of a few percent. In the HIGS instrument this band is selected using a bandpass filter. Within this band spectral lines are present with a periodicity of about 4nm, determined by the gas molecular properties. Using an interferometer a filter is created that closely matches this periodicity, increasing our sensitivity to this specific gas property.

In the HIGS instrument two identical images of the Earth are passed through this filter and imaged onto a single sensor. Here one image contains the destructively interfering signal, whereas the second image contains the constructively interfering image, see Fig. 2. Hereby an instantaneous image is provided where the signal modulation provides a measure for the gas concentration, independent of the actual signal level. Multiple measurements can be averaged to enhance the SNR further.



**Fig. 2.** Schematic illustration of the HIGS measurement principle

The interferometer spectral pixel intensity  $I_c$  and  $I_d$  can be describes by (1) and (2) for constructive and destructive interference respectively.

$$I_c = \int_{\lambda_s}^{\lambda_e} 2 \cdot \sqrt{I_1(\lambda) \cdot I_2(\lambda)} \cdot \cos\left(\frac{OPD \cdot 2 \cdot \pi}{\lambda}\right) + I_1(\lambda) + I_2(\lambda) d\lambda \quad (1)$$

$$I_d = \int_{\lambda_s}^{\lambda_e} 2 \cdot \sqrt{I_1(\lambda) \cdot I_2(\lambda)} \cdot \cos\left(\frac{[OPD + \frac{1}{2}\lambda] \cdot 2 \cdot \pi}{\lambda}\right) + I_1(\lambda) + I_2(\lambda) d\lambda \quad (2)$$

Here  $I_{1,2}$  are the signals created by the beam splitter from the incoming images IMG A and B,  $\lambda$  is the wavelength,  $\lambda_s$  and  $\lambda_e$  are respectively the start and end wavelength from the passband of the filter and OPD is the optical path difference between the interferometer arms.

From these signals the NO<sub>2</sub>-gas induced contrast  $\gamma$  is determined:

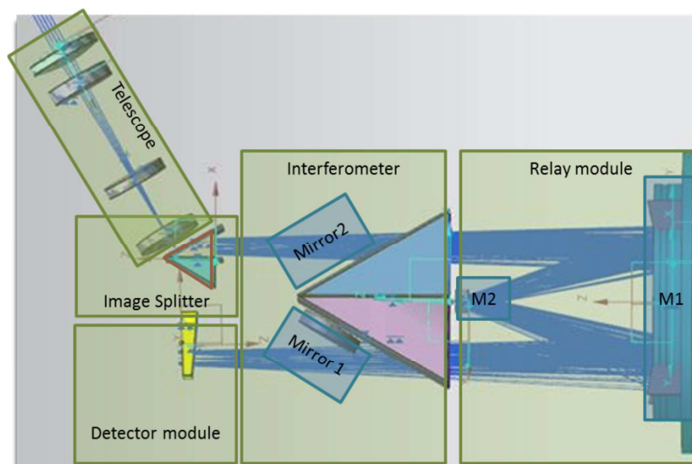
$$\gamma = \frac{I_c - I_d}{I_c + I_d} \quad (3)$$

This contrast is directly proportional to the light absorption by the observed atmosphere column, which in turn is proportional to the molecular cross section and the column density for low gas concentrations. In our case this parameter describing the relation between observed contrast and gas column density is validated experimentally.

Altogether a compact imaging concept is defined, which provides instantaneous gas concentration measurements. To the first order these results are insensitive to the light intensity or presence of other gases.

## II. DEMONSTRATOR DESIGN

Following an extensive design study a demonstrator of the HIGS system was realized, targeting demonstration of NO<sub>2</sub> concentration imaging. This demonstrator is based on an optical design for a geostationary mission but realized as an advanced laboratory breadboard, comprising custom optical components and coatings, commercial camera and aluminum mechanical parts. The optical design, see Fig. 3 consists of five main building blocks.



**Fig. 3.** Optical layout of the HIGS breadboard for NO<sub>2</sub> detection

The telescope design used here is a two-singlet imager, designed for a 10degree field of view (FOV). Bandpass filters are included in this section as well. This telescope section provides a diffraction limited image of Earth on an entrance aperture of the image splitter section. Also telescopes for a Low Earth Orbit (LEO) were designed, yet seemed less practical for on ground validation and hence not selected for the demonstrator.

Using a beam splitter the Earth image is doubled. These two identical images are transmitted throughout the rest of the optics as a single image and are used later to simplify the measurement.

The relay module presented here is a mirror based relay group that is used twice. First to reposition the images into the interferometer and next relay the images onto the detector. As the optical path is folded and build-up in several layers a simplified path is depicted in the figure.

Core of the system operation is the interferometer, which is used as a static, fixed Optical Path Difference (OPD) FTS. Here the OPD is tuned to provide the spectral transmission matching the gas absorption lines for the first image. As a result a constructive signal proportional to the gas concentration will result. In the second image an additional fixed phase step of half a wavelength is applied, so that the gas signal in this image always interferes destructively. For alignment and experimental purposes a manually controlled tip-tilt and piezo controlled mirrors are implemented.

On the camera two identical images are detected next to each other. The intensity differences between these images directly translates to the gas absorption.

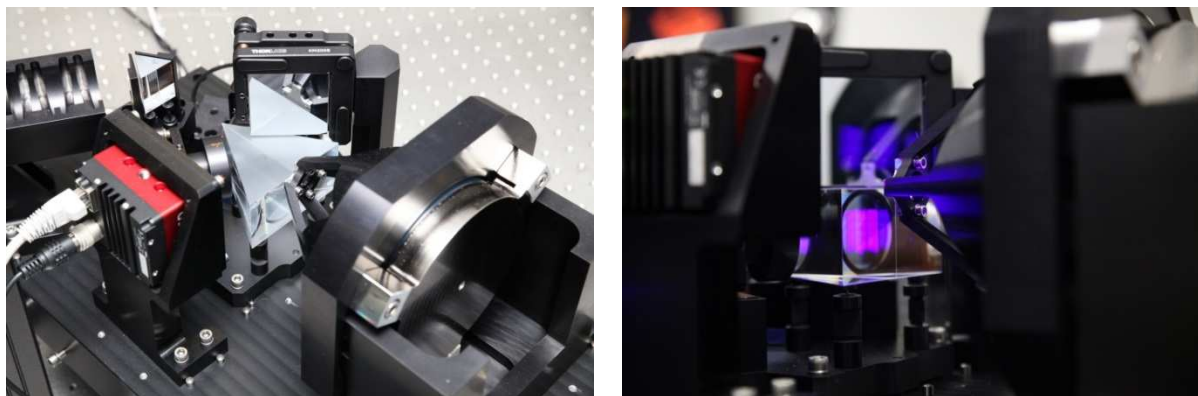


Fig. 4. HIGS breadboard pictures

The breadboard is controlled using matlab on a PC. Mirror alignment can be varied by changing Piezo settings and recorded images are further processed.

### III. EXPERIMENTAL VALIDATION

Several instrument properties are validated experimentally to enable operation of the system. This comprises the optical alignment, imaging performance, interferometer characterization and the measurement sensitivity (gain) of the NO<sub>2</sub> gas.

#### A. Optical alignment and determination of instrument parameters

Validation and adjustment of the optics angular alignment is performed using a theodolite assuring alignment of the optics to few arcseconds level. Positioning of alignment sensitive optics (relay group mirrors) is guaranteed by production tolerances. Focus adjustments are performed manually by maximizing the image contrast. These adjustment are sufficient to achieve the imaging performance of the instrument. (See Fig. 5)

Most critical is the interferometer alignment, as here OPD variations in the order of tens of nm significantly influence the instrument contrast. Here a two-step approach is pursued. As a first step a long stroke scan is performed (normal FTS operation) allowing determination of the zero-OPD point (See Fig 5.) as well as the spectral transmission and the optics imperfections. This is followed by fine angular alignment and introducing the desired OPD to the IFM.

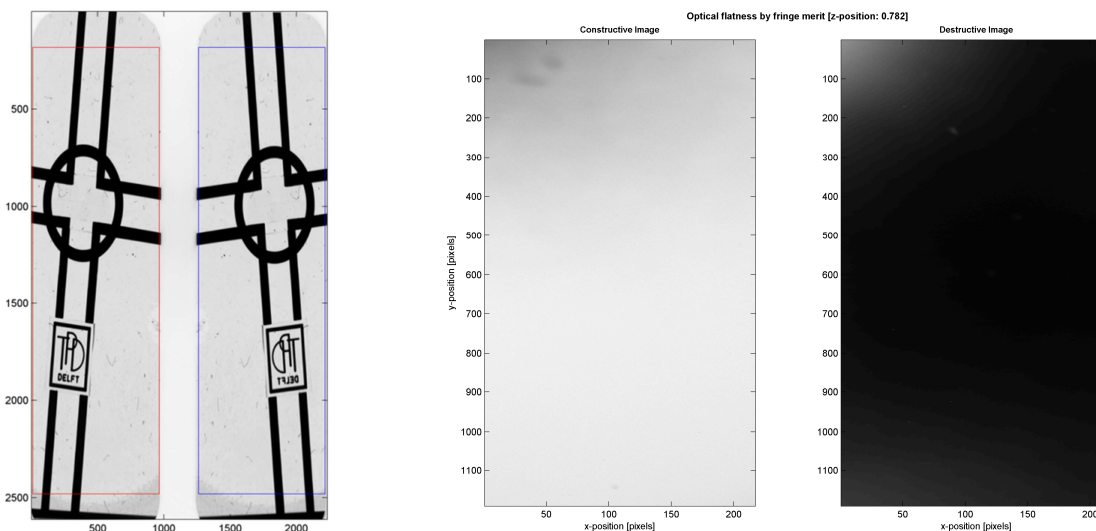
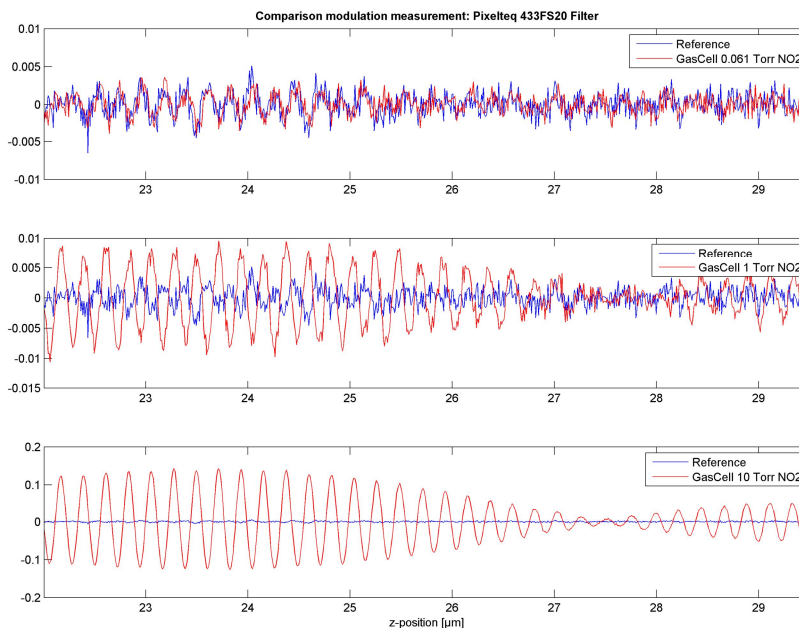


Fig. 5. Left: Raw image on test target for co-registration determination. Right: Constructive and destructively interfering images to assess optics flatness

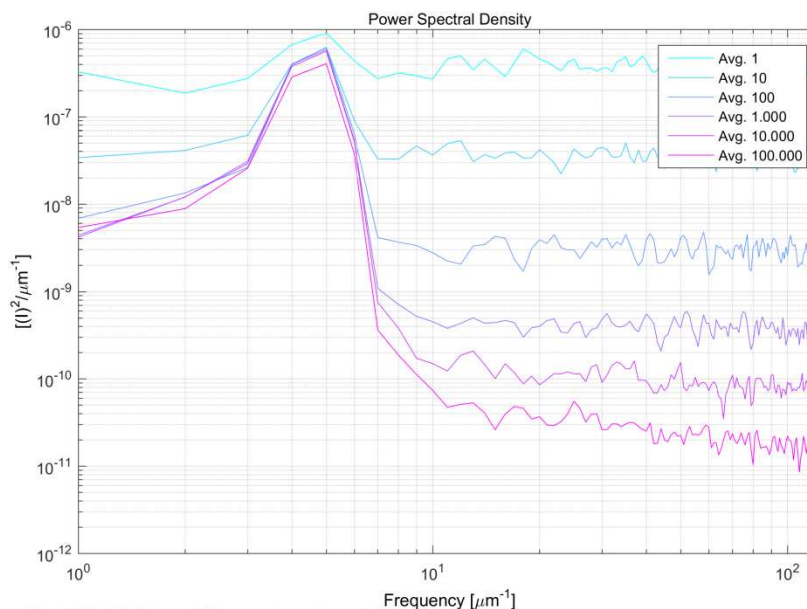
#### B. Measurement performance assessment on gas cells

NO<sub>2</sub> filled gas cells are used with several concentration level to assess the instrument response. Using OPD-scans both the gain factor as the ideal OPD setting for the measurement are determined. (See Fig. 6)



**Fig. 6.** Measured contrast as a function of mechanical path difference for gas cells with three different concentrations.

From Fig. 6 it should be noted that the contrast levels in the measurements are low in general (as expected), stressing the need for proper instrument characterization in terms of gain and background signals. On the lowest concentration gas cell an averaging experiment was performed to assess to what extent the measurement was limited by the signal level or the instrument. (See Fig. 7.)

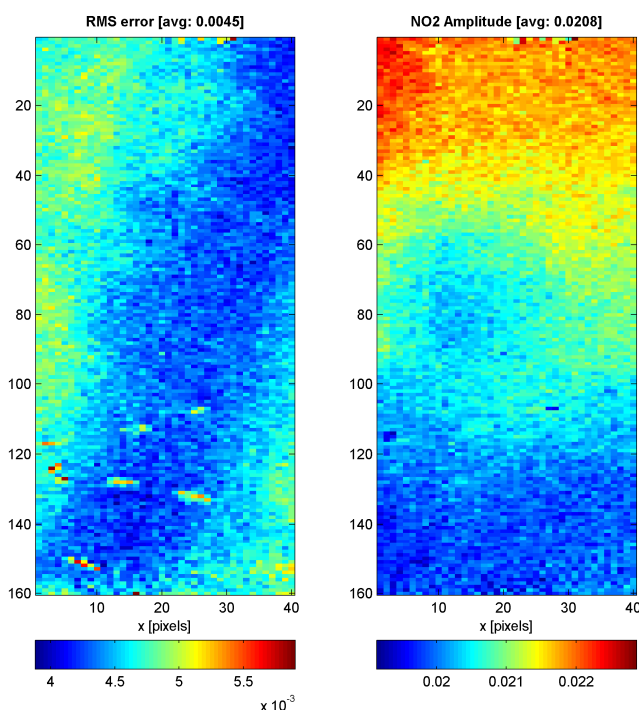


**Fig. 7.** Contrast values as a function of degree of averaging and spatial frequency (pixel scale).

The PSD shows a clear peak around 4-5 nm periodicity, matching half the center wavelength of 440nm (220 nm), indicating the presence of NO2. The peak is becoming more and more apparent when averaging is applied. Main result of this measurement is that although SNR's in individual measurements can be very low the measurements are not limited by the optical-mechanical instrument itself. This demonstrates the actual instrument works sufficiently well and that using these instrument dimension, some averaging/binning is required to achieve the desired measurement accuracy, which was anticipated.

### C. On sky measurement

Although long term on-sky measurement against reference systems has not been performed yet, some initial measurements were performed.



**Fig. 8.** First on-sky measurement, showing contrast on the left, measurement noise, and un-scaled NO<sub>2</sub> concentration on the right. The top of the image is the horizon at approximately 7°, so the image is visualized up-side-down

Although Fig. 8 does not provide an quantitative result, in the NO<sub>2</sub> Amplitude sub image the expected gradient due to the path length variation is clearly visible. Additional on-sky measurements are in preparation. Here a multi-day measurement campaign is being prepared in collaboration with the Dutch Meteorological institute (KNMI), where the HIGS instrument will be benchmarked against a traditional NO<sub>2</sub> measurement technique (MAX DOAS).

#### IV. CONCLUSIONS AND RECOMMENDATIONS

A new measurement concept for the determination of gases concentrations in the Earth atmosphere is presented. This approach allows for instantaneous gas concentration measurements with better ground resolution or smaller instrument volume than current spectrometers, for reference the demonstrator has an size of 420 x 250 x 250mm.

Several optical designs have been studied and analyzed for performances and one design has been realized as a demonstrator. Experiments on NO<sub>2</sub>-filled gas cells have been performed already on the breadboard, demonstrating the validity of the concept. NO<sub>2</sub> gas can indeed be detected by this method and the measurement sensitivity is not limited by the optical system.

Altogether this new HIGS instrument seems to be an interesting candidate for future Earth observation space missions. Here a first step in the further development is the on-sky demonstration and benchmarking of the instrument, which is foreseen later this year.

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