International Winds Workshop #10, Tokyo, Japan, 22-26 February 2010

SMVs (STEREO MOTION VECTORS) FROM ATSR2-AATSR AND MISRlite (MULTI-ANGLE INFRARED STEREO RADIOMETER) CONSTELLATION

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Abstract

The NASA MISR (Multiangle Imaging Spectro-Radiometer) has been employed to produce a ten year time series of cloud-top heights and winds (Stereo Motion Vectors, SMVs) using the stereo matching system described by [1]. A review will be presented of different validation approaches for cloud-top heights which have been assessed. These indicate that ground-based radar and lidar systems such as those employed by the Chilbolton Radar Facility for Atmospheric Research are optimal for such purposes.

Independent work suggests that for both radiosonde and Doppler wind match-ups, accuracies are within the specification of 3 m/s RMS and from the CFARR and ARM analyses that cloud-top heights are within 600m RMS.

Results are presented on a preliminary assessment of obtaining SMVs from ATSR2 and AATSR across-track wind component as well as from tracking ATSR2-AATSR 30 minute time interval imagery using the ATSR2 stereo processing system described in [2].

Taking as our starting point, the MISR follow-on WindCam concept described in [3], we have developed a breadboard system using INO® uncooled microbolometers which we call MISRlite (Multi-angle Infra-red Stereo Radiometer). MISRlite aims to retrieve winds and heights irrespective of solar illumination for use in improving NWP and severe weather forecasts as well as improve our understanding of severe weather systems such as hurricanes and storm fronts. Initial laboratory and field results will be shown of MISRlite and a preliminary assessment made of a constellation system for obtaining global wind-fields with ≤3m/s and ≤300m RMS height errors.

CONTEXT AND INTRODUCTION

The need for synoptic-scale wind information with sufficiently accurate cloud-top heights and winds is well documented in the International Winds workshop since it began in 1990. Existing methods for the retrieval of Atmospheric Motion Vectors (SMVs) mostly rely on tracking of clouds at thermal IR and/or visible wavelengths and tracking patterns in Water Vapour (WV). For cloud-tracking, heights are assigned based on the IR channel brightness temperature and the use of objective analysis based on radiosondes or gridded NWP analysis fields [4]. Although methods for cloud-tracking and resolution have significantly improved over the last decades, the fundamental method for SMV height assignment has barely changed over the last 50 years.

In contrast, stereo photogrammetric retrievals of cloud-top heights do not depend on any external information such as Objective Analysis (OA) fields. They were first demonstrated with geostationary images from the GOES-East and West satellites [5-8] and proposed for use with the ATSR (Along Track Scanning Radiometer) instrument onboard the European ERS-1 satellite in 1985 [9]. They were first demonstrated with ATSR data by [10, 11]. The MISR (Multi-angle Imaging SpectroRadiometer) instrument was launched in December 1999 and for more than a decade has been operationally producing Stereo Motion Vectors (SMVs) using the computer vision methods described by [1, 12] which were only very recently modified to obtain better coverage of winds (K. Mueller & M. Garay, JPL, private communication).

MISR CTH AND SMV ASSESSMENT

Most effort to date has focused on Cloud-Top Height (CTH) assessment with the MISR Top-of-Atmosphere Cloud product. Several authors have compared MISR CTHs with cloud boundaries retrieved from combined ground-based radar and lidar [13-16]. These studies all indicate that over a wide range of weather conditions, CTHs are retrieved with an accuracy of 0.05±0.62km for single layer clouds of cloud optical depth ≥0.01 showing there is only a very small bias with standard deviations around the theoretical value predicted by [1] of 560m. In contrast, [17] showed that radar/lidar cf. radiosondes for CTH show 0.35±0.73km. This should be compared with a value of some 300m±1.2km for MODIS CTHs for cloud optical depths ≥0.3 [18].

More recently, [19] used Doppler wind data records from 23 of the US NWS Doppler wind profilers to assess the MISR wind retrievals and found agreement of -0.27±3.61m/s with better agreement for the zonal component compared with the meridional component.

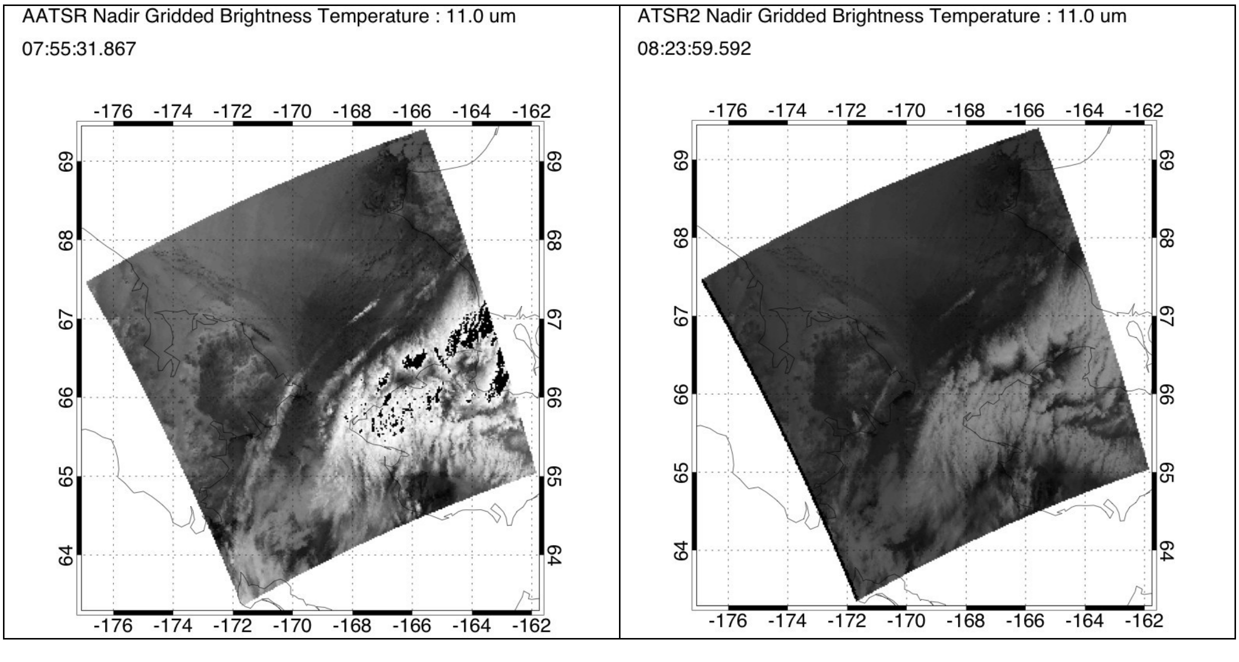
ATSR-AATSR SMVs

[10] first demonstrated the feasibility of obtaining single (across-track) wind components from ATSR stereoscopy with a height accuracy of about 1 km in mean cloud-top heights and ±8 ms in wind speed using a single pixel acuity stereo matching technique. From the launch of the ENVISAT platform in March 2002, AATSR was able to acquire imagery within 30 minutes of ATSR2 for the time period from June 2002-July 2003. This so-called tandem acquisition presents the possibility of obtaining single component (across-track) winds from ATSR2 and AATSR separately (loc.cit.) as well as both wind components from tracking cloud features between ATSR2 and AATSR.

[2] demonstrated that fast and effective stereo cloud-top height could be routinely obtained from (A)ATSR(2) using automated stereo photogrammetry for large areas and [20] showed that over two different ground-based radar and lidar sites, cloud-top heights could be obtained with an accuracy of -350m±1km using the 11µm channel. Less work has been published on the assessment of cloud-top winds aside from the previously quoted results from [10].

Herein we apply the stereo matching technique to the retrieval of the across-track wind component from successive ATSR2 and AATSR stereo-pairs. Only the 11µm channel is employed but the same approach could be applied to any of the 7 (A)ATSR(2) channels, subject to the solar zenith angle being sufficiently large for the solar reflective channels.

In Figure 1, the two input ATSR2 and AATSR nadir images are shown along with the cloud-top heights derived using the stereo methods described in [2].



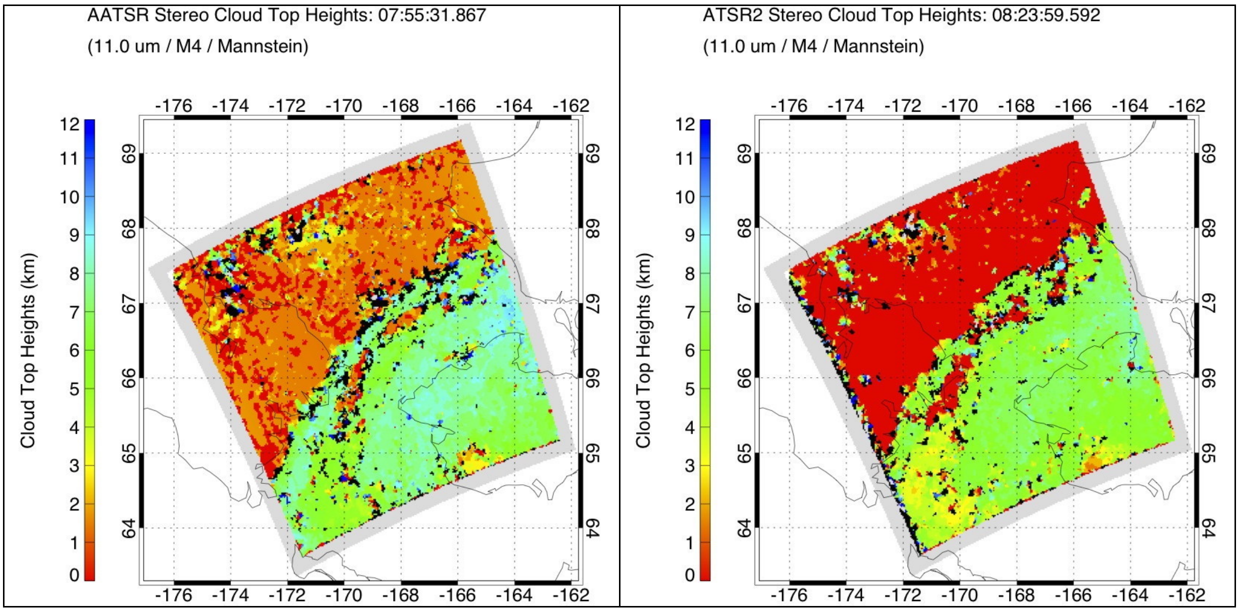
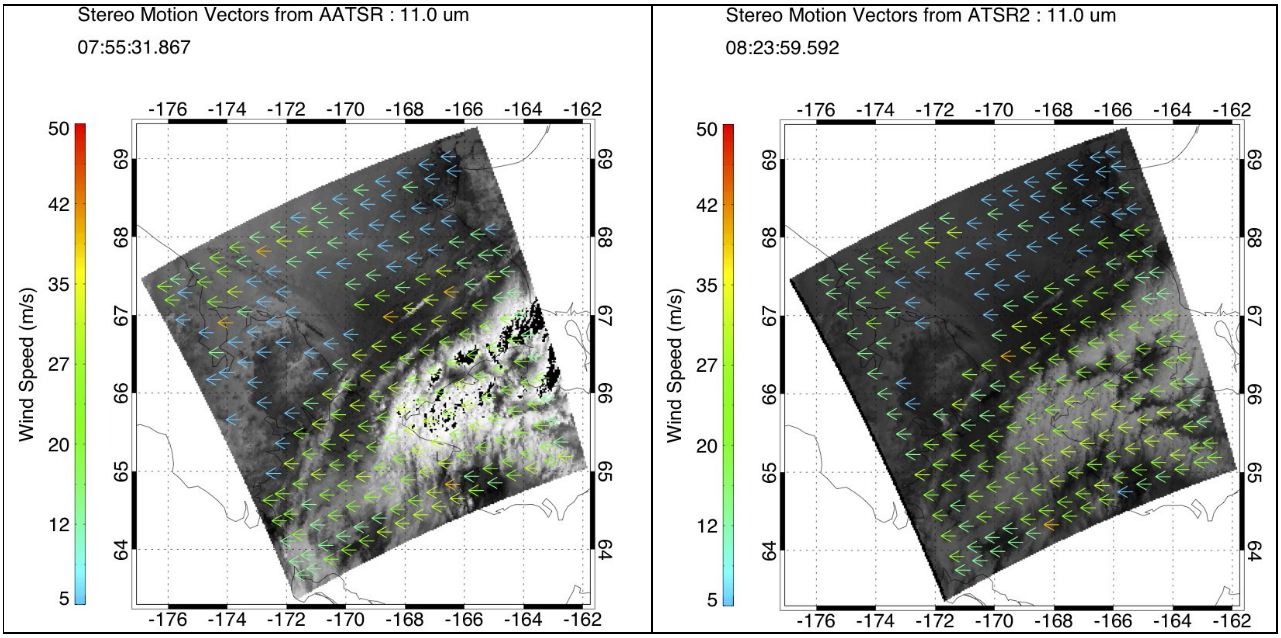


Figure 1. AATSR and ATSR 11µm nadir images (upper panels) and corresponding Cloud-Top Heights (CTH) generated from nadir and forward view acquired within 30 minutes of each on 18 January 2003

There are small changes visible in the low level clouds which may be due to the pixel-level acuity and approximations to the stereo imaging geometry employed in their modelling. However, the differences are <1km but may be due to the fact that low level optically thin cloud cleared in the 30 minutes between images. In fact the heights are within a few hundred metres of each other which is well within the height precision of the DEM.

[10] showed that in addition to the retrieval of cloud-top height, ATSR2 data could be employed to retrieve across-track wind component. Using this method, the Stereo Motion Vector component in the across-track direction (SMV-xtrack) was retrieved from each of the ATSR2 and AATSR stereo images. The results of this SMV-xtrack are shown in Figure 2 alongside a stereo red/blue anaglyph and the retrieved full SMVs by tracking clouds between the 2 nadir acquisitions taken 30 minutes apart in the usual manner.



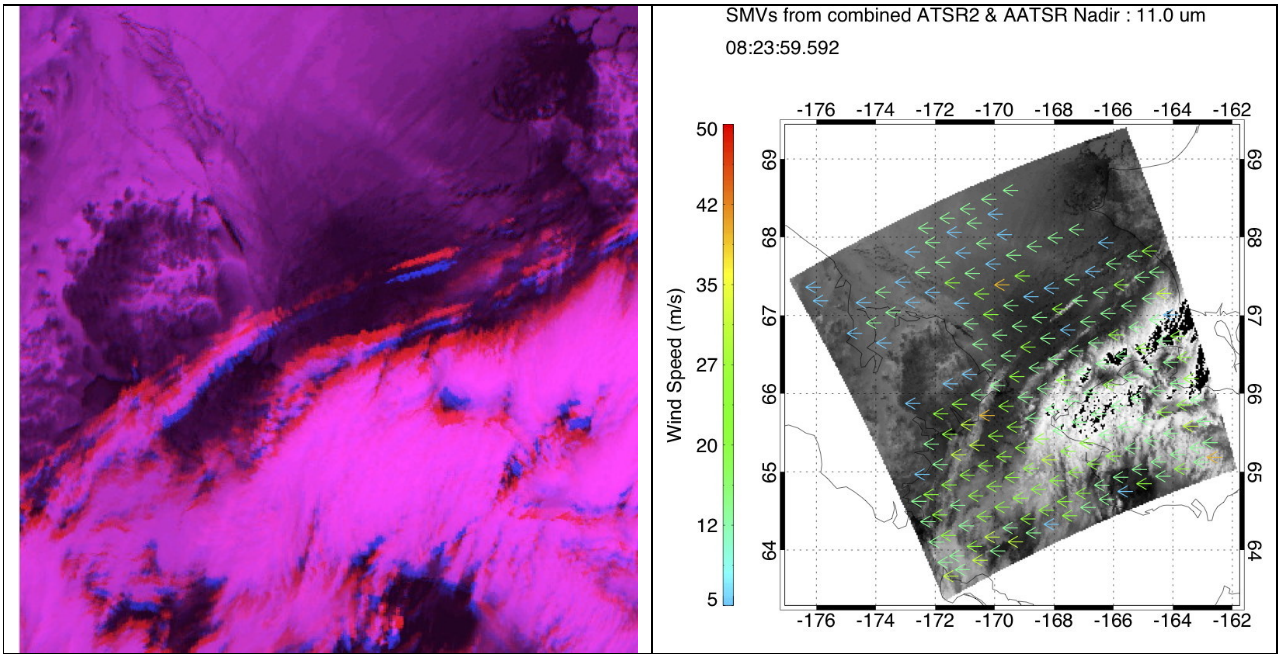


Figure 2. Stereo Motion Vector (SMV) winds from AATSR (upper left), ATSR2 (upper right) and from tracking the same features in the nadir image with height values acquired from the DEMs shown in the lower portion of Figure 1. Red/Blue Anaglyph of AATSR shown in the lower right. To view this anaglyph in stereo, a rotation angle of 90 degrees is required ©UCL 2010

The statistics of each of the SMVs is given in Table 1. Inspection shows that overall the SMVs for ATSR2 and AATSR are very close in value whereas the AATSR-ATSR2 is somewhat different.

	Mean SMV speed	Standard deviation SMV speed
AATSR	18.89	10.33
ATSR2	18.74	10.89
AATSR-ATSR2	14.02	9.21

Table 1. Intercomparison of wind statistics for 3 different SMV extractions from tandem ATSR2-AATSR images

The moderate spatial resolution (1:1.7km for nadir:forward) and time difference (2 minutes) limits the height accuracy to around 1km and the wind-speed accuracy to 8 m/sec (loc.cit.). For the time difference (ATSR2-AATSR), absolute accuracy of wind-speed will be similar (i.e. 1km/2 minutes). The lower mean SMV speed of AATSR-ATSR2 is caused by fewer matches obtained for clouds with higher wind speeds likely deforming, particularly in regions of optically thin cloud. This low inherent accuracy will limit the application of ATSR2-AATSR. However, if in future there might be two Sentinel-3 spacecraft in orbit with similar characteristics with an identical SLSTR (successor to AATSR family with 750km of swath overlap and 500m resolution) then twice the SMV windspeed accuracy might be possible (≈4m/sec) with 500m CTH resolution.

Stereo Motion Vectors (SMVs) from MISRlite

[3] described the WindCam concept for a follow-on mission to MISR using a low cost (5% of original MISR cost) visible optical system operating at red wavelengths in a sun-synchronous orbit with 300m spatial resolution and a swath-width of 1,000km. A constellation of three WindCam instruments in polar Earth orbit could obtain height-resolved SMVs with daily global coverage, making it a low-cost complement to the lidar 3-D Winds mission envisioned by the EUMETSAT Post-EPS mission scenarios as well as the National Research Council's Earth Sciences Decadal Survey. However, the need for sun-synchronous acquisitions limit the utility of such a WindCam system to less than half of their orbits each day. In addition, much high level cloud is missed from such visible-only systems.

The Multiangle Stereo IR Radiometer (MISRlite) is a follow-on concept from WindCam which uses uncooled microbolometer technology to obtain 5 looks using the same optics, a curved focal plane to try to obtain fairly equal sized pixels in all looks, 300m pixels and 1500km swath. MISRlite is planned to fly on a non sun synchronous platform, allowing SMV retrievals to be obtained day and night irrespective of illumination conditions. The primary aim of MISRlite is to obtain SMVs using a similar approach to MISR and what was proposed for WindCam. However, sub-pixel matching will be applied in the ground processing stream and it is envisaged that an onboard processing system will permit the generation of SMVs several minutes after image acquisition for direct ingestion into NWP forecasting and nowcasting models.

A breadboard system development funded by the UK NERC CEOI (Centre for EO Instrumentation) has recently been completed. Figure 3 shows the breadboard sensor test rig provided by INO® with the characteristics of this sample sensor shown in Table 2. A 3-line uncooled thermal IR linear array of 512 elements, sealed in a ceramic vacuum-evacuated container, has been tested in the laboratory at MSSL. The test system consists of a scanning front-silvered mirror with an off-the-shelf IR Ge lens, with similar characteristics interfaced to the INO sensor. The wide-angle optics were designed to mimic the final system, designed by our colleagues at the UK Astronomy Technology Centre in Edinburgh.

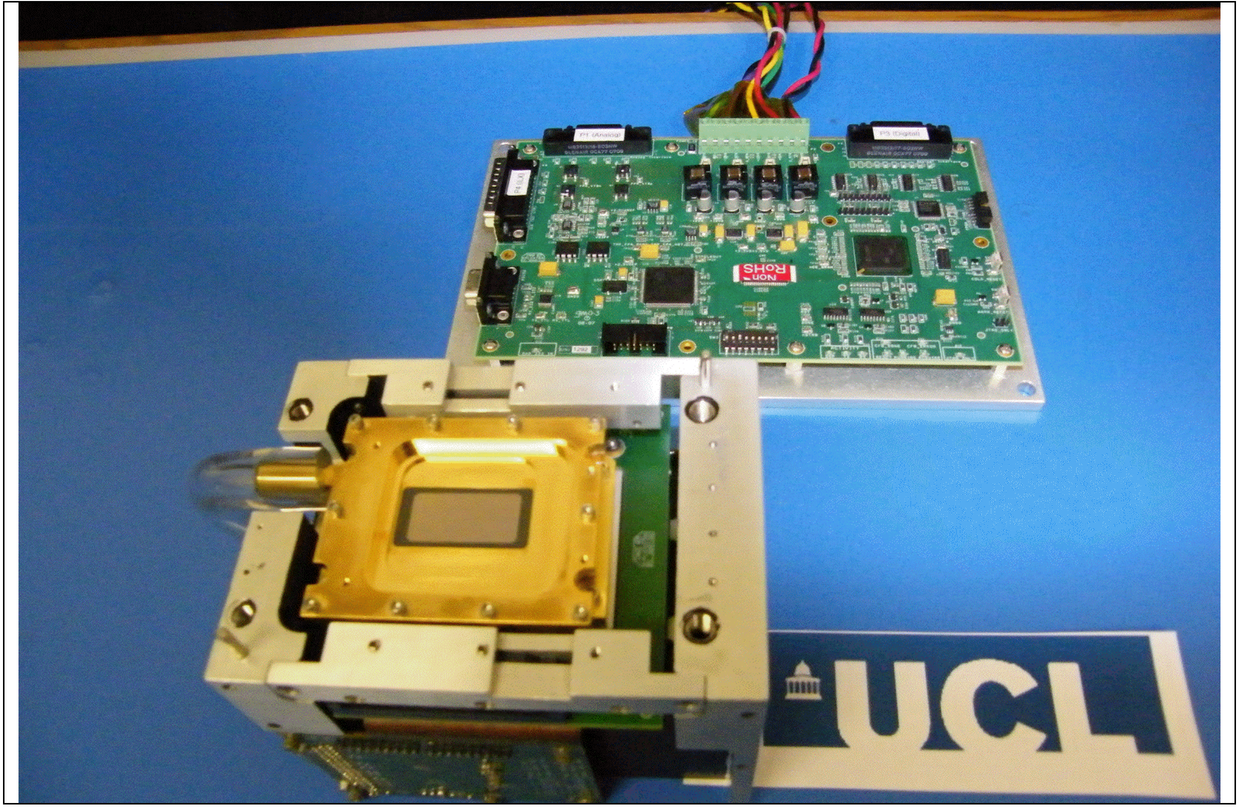
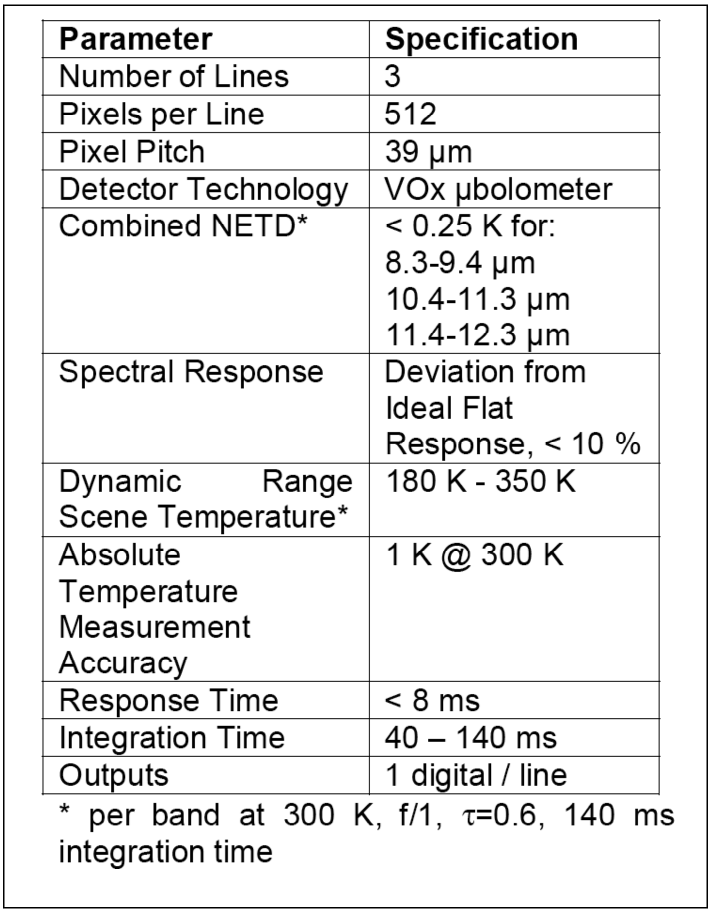


Figure 3. INO® microbolometer sensor and control electronics for testing at UCL-MSSL. For characteristics, see Table 2.

INO® are currently developing a 2500 pixel array and it is this larger size (or even larger) that is preferred for the final system. INO® originally developed this thermal IR sensor for a 256 x 40 array for a joint Argentinian-Canadian forest fire detection system and this accounts for the 3 wavelengths selected. MISRlite will use a multi-spectral imaging array at nadir (i.e. 3-lines at nadir but only 2 off-nadir in the fore and 2 off-nadir aft). The multispectral 3 line sensor can be applied for a secondary science objectives related to (a) detection of volcanic SO2, dust or ash [21-23]; (b) detection of aircraft condensation trails, or “contrails” [24] [25]; (c) detection of forest fires; (d) mapping of urban heat island effects on a daily basis; (e) Sea Surface Temperature monitoring of large-scale synoptic-scale development. However, the eventual MISRlite sensor will not include any onboard calibration, only limited preflight calibration as the primary goal is to maximize contrast and image texture needed to obtain the best possible matching and not obtain absolutely radiometrically calibrated data.



Parameter	Specification
Number of Lines	3
Pixels per Line	512
Pixel Pitch	39 µm
Detector Technology	VOx µbolometer
Combined NETD*	< 0.25 K for: 8.3-9.4 µm 10.4-11.3 µm 11.4-12.3 µm
Spectral Response	Deviation from Ideal Flat Response, < 10 %
Dynamic Range Scene Temperature*	180 K - 350 K
Absolute Temperature Measurement Accuracy	1 K @ 300 K
Response Time	< 8 ms
Integration Time	40 – 140 ms
Outputs	1 digital / line

* per band at 300 K, f/1, τ=0.6, 140 ms integration time

Table 2. Characteristics of the INO® microbolometer system taken from [26]

Figure 4. INO® microbolometer array from the UCL-MSSL test system of clouds (upper) and trees (lower). The 512-pixel array was scanned using a slow scanning mirror (3-4 minutes for a 1000 line scan). The sole artifact visible is the striping artifact.

Figure 4 shows an example image taken by this test system of a cloud complex by staring out of the window of the optics laboratory. A small residual striping can be seen in the image. Aside from this no other artifact is visible. The contrast is low so the final system needs to have a smaller NEdT, probably around 5-8 times better than at present.

The MISRlite instrument forms a central role for the proposed future WINDS platform to be submitted to the ESA Earth Explorer Call number 8. This will include onboard data processing of SMVs, direct broadcast of SMVs and fusion with an Oxygen A-band nadir pointing instrument for aerosols. This proposed pre-operational system will be used to test the best possible strategy of how to create a constellation of low cost platforms dedicated to the creation of global SMVs for the improvement of NWP forecasts including severe storms (see D. Wu et al., 2010; this proceedings).

References Cited

[1] J.P. Muller, A. Mandanayake, C. Moroney, R. Davies, D.J. Diner, S. Paradise, MISR stereoscopic image matchers: Techniques and results, IEEE Trans. Geosci. Remote Sensing 40(2002) 1547-1559.

[2] J. Muller, M. Denis, R.D. Dundas, K.L. Mitchell, C. Naud, H. Mannstein, Stereo cloud-top heights and cloud fraction retrieval from ATSR-2, Int. J. Remote Sens. 28, 2007, pp. 1921-1938.

[3] D.J. Diner, M. Mischna, R.A. Chipman, A. Davis, B. Cairns, R. Davies, R.A. Kahn, J.-P. Muller, O. Torres, WindCam and MSPI: two cloud and aerosol instrument concepts derived from Terra/MISR heritage, in: J.J. Butler, J. Xiong, (Eds), SPIE Earth Observing Systems XIII 7081, SPIE, San Diego, 2008, pp. 70810T-70810T-70819.

[4] R.W. Saunders, Cloud-top temperature/height: A high-resolution imagery product from AVHRR data. , Meteorological Magazine 117(1988).

[5] A.F. Hasler, K. Palaniappan, C. Kambhammetu, P. Black, E. Uhlhorn, D. Chesters, High-resolution wind fields within the inner core and eye of a mature tropical cyclone from GOES 1-min images, Bull. Amer. Meteorol. Soc. 79(1998) 2483-2496.

[6] A.F. Hasler, K.R. Morris, Hurricane structure and wind fields from stereoscopic and Infrared satellite observations and radar data, J. Climate & Appl. Meteor. 25(1986) 709-727.

[7] E.B. Rodgers, R. Mack, A.F. Hasler, A satellite stereoscopic technique to estimate tropical Cyclone intensity., Mon. Wea. Rev. 111(1983) 1599-1610.

[8] A.F. Hasler, Stereographic observations from satellites: An important new tool for the atmospheric sciences., Bull. Amer. Meteor. Soc. 62(1981) 194-212.

[9] D. Lorenz, On the feasibility of cloud stereoscopy and wind determination with the Along-Track Scanning Radiometer, Int. J. Rem. Sens. 6(1985) 1445-1461.

[10] A.J. Prata, P.J. Turner, Cloud-top height determination using ATSR data, Rem. Sens. Env. 59(1997) 1-13.

[11] D. Shin, J.K. Pollard, Cloud height determination from satellite stereo images, *IEE Colloquium on Image Processing for Remote Sensing,* 13 Feb 1996, IEE, IEE Savoy Place, 1996, pp. 4/1-4/7.

[12] C. Moroney, R. Davies, J.P. Muller, Operational retrieval of cloud-top heights using MISR data, IEEE Trans. Geosci. Remote Sensing 40(2002) 1532-1540.

[13] C.M. Naud, J.P. Muller, E.C. Slack, C.L. Wrench, E.E. Clothiaux, Assessment of the performance of the Chilbolton 3-GHz advanced meteorological radar for cloud-top-height retrieval, Journal of Applied Meteorology 44, 2005, pp. 876-887.

[14] C. Naud, J.P. Muller, M. Haeffelin, Y. Morille, A. Delaval, Assessment of MISR and MODIS cloud top heights through intercomparison with a back-scattering lidar at SIRTA, Geophys. Res. Lett. 31(2004) art. no.-L04114.

[15] J. Zong, R. Davies, J.P. Muller, D.J. Diner, Photogrammetric retrieval of cloud advection and top height from the multi-angle imaging spectroradiometer (MISR), Photogramm. Eng. Remote Sens. 68(2002) 821-829.

[16] C. Naud, J.P. Muller, E.E. Clothiaux, Comparison of cloud top heights derived from MISR stereo and MODIS CO2-slicing, Geophys. Res. Lett. 29(2002) art. no.-1795.

[17] C.M. Naud, J.P. Muller, E.E. Clothiaux, Comparison between active sensor and radiosonde cloud boundaries over the ARM Southern Great Plains site, J. Geophys. Res.-Atmos. 108(2003) art. no.-4140.

[18] C. Naud, J.P. Muller, P. de Valk, On the use of ICESAT-GLAS measurements for MODIS and SEVIRI cloud-top height accuracy assessment, Geophys Res Lett 32, 2005, p. L19815.

[19] L.N. Hinkelman, R.T. Marchand, T.P. Ackerman, Evaluation of Multiangle Imaging Spectroradiometer cloud motion vectors using NOAA radar wind profiler data, J. Geophys. Res 114(2009) 12.

[20] C. Naud, J. Muller, E.E. Clothiaux, Assessment of multispectral ATSR2 stereo cloud-top height retrievals, Remote Sens. Environ. 104, 2006, pp. 337-345.

[21] M.A.M. Novak, I.M. Watson, H. Delgado-Granados, W.I. Rose, L. Cardenas-Gonzalez, V.J. Realmuto, Volcanic emissions from Popocatepetl volcano, Mexico, quantified using Moderate Resolution Imaging Spectroradiometer (MODIS) infrared data: A case study of the December 2000-January 2001 emissions, J Volcanol Geoth Res 170(2008) 76-85.

[22] E.B. Mccarthy, G.J.S. Bluth, I.M. Watson, A. Tupper, Detection and analysis of the volcanic clouds associated with the 18 and 28 August 2000 eruptions of Miyakejima volcano, Japan, Int. J. Remote Sens. 29(2008) 6597-6620.

[23] M. Doutriaux-Boucher, P. Dubuisson, Detection of volcanic SO2 by spaceborne infrared radiometers, Atmos Res 92(2009) 69-79.

[24] J.Q. DeGrand, A.M. Carleton, D.J. Travis, P.J. Lamb, A satellite-based climatic description of jet aircraft contrails and associations with atmospheric conditions, 1977-79, J. Appl. Meteorol. 39(2000) 1434-1459.

[25] R. Meerkötter, C. König, P. Bissolli, G. Gesell, H. Mannstein, A 14-year European Cloud Climatology from NOAA/AVHRR data in comparison to surface observations, Geophys Res Lett 31(2004).

[26] T. Pope, C. Chevalier, C. Alain, A. Bergeron, 512x3 PIXEL UNCOOLED FPA FOR THERMAL INFRARED PUSHBROOM IMAGING, IAC-04-IAF-B. 3.08