Predictors of measurement accuracy in the remote sensing of CO_2 emissions

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ABSTRACT

Remote sensing confers several advantages over ground-based measurements that make it an important tool for developing CO_2 emissions inventories. Anthropogenic CO_2 monitoring requires a high degree of accuracy in order to detect changes against the natural background variations of CO_2. While studies indicate that some satellites already have this level of CO_2 measurement accuracy, it is unclear what instrument properties might be responsible. Satellite instruments have been designed with a wide variety of spatial, temporal, and spectral resolutions depending on their original mission objectives, and any one or more of these properties might allow for a high CO_2 measurement accuracy. The goal of this work was to determine whether any instrument properties might be good predictors of CO_2 measurement accuracy, since this information would be useful for the design of future satellite instruments for monitoring CO_2 emissions. The instrument properties of 25 current and planned satellite missions up to 2020 were compiled, alongside studies demonstrating the CO_2 measurement accuracy of these instruments. Using multiple linear regression models, the combination of spatial resolution and swath width was found to be a significant predictor of CO_2 measurement accuracy. The most accurate satellite instruments are also described, as well as suggestions for improving existing CO_2 emissions inventories by combining their data with ground measurements.

INTRODUCTION

To perform CO_2 emissions inventories, ideally every emissions source should be accounted for. This is where remote sensing can be a powerful tool. Satellites can measure CO_2 from places where ground monitoring is impractical or infeasible, and could provide a check on ground-measured emissions once calibrated by ground truthing. Simultaneous CO_2 measurements can be done over a large area, limited only by the satellite instrument's swath width. A snapshot of CO_2 over the earth can easily be done from space, whereas it would require a massive network of ground-based CO_2 monitors to achieve the same coverage from the ground.

While remote sensing would seem to be a powerful tool for CO_2 emissions inventories, it is notable that none of the existing satellite instruments were designed to monitor strong anthropogenic CO_2 emissions from space. Instead, they were meant to provide additional constraints on natural CO_2 sources and sinks, or had different mission objectives altogether (Bovensmann *et al.* 2010). As an example, the SCIAMACHY instrument can detect atmospheric CO_2 with 2.5 ppmv accuracy, but was designed for the detection of a variety of trace gases (Reuter *et al.* 2011). The first space mission designed specifically for CO_2 monitoring was GOSAT, which did not launch until 2009 (Crevoisier *et al.* 2009). However, its spatial resolution is too coarse to be able to resolve the fine details of anthropogenic emissions sources. To resolve the structure of CO_2 plumes from coal-fired power plants, a spatial resolution of 2x2 km (4 km^2) was found to be necessary (Bovensmann *et al.* 2010). This resolution is planned for the CarbonSat instrument, which will not be ready for launch until 2018.

Satellite instruments with CO_2-sensing capability are able to measure CO_2 concentration with varying degrees of accuracy. This raises the question of what factors might be responsible for the high level of accuracy necessary for monitoring anthropogenic CO_2 emissions. A clear sky free of scattering due to aerosols and cirrus clouds lends itself to more accurate CO_2 measurements (Aben *et al.* 2007). However, not much is known about what specific properties of an instrument might enable it to achieve high measurement accuracy. If this information were known, this would help inform the design of future satellite missions for monitoring anthropogenic CO_2 emissions. The goal of this work was to determine whether there were any properties of existing or planned satellite instruments that might be good predictors of CO_2 measurement accuracy.

APPROACH

An initial list of CO_2-sensing satellite instruments was developed by searching the CEOS satellite instrument database of the European Space Agency for instruments capable of detecting CO_2 (ESA 2011). A total of 25 existing and planned missions up until 2020 were found, with 15 total instruments (Table 1); some instruments are planned to be reused on multiple missions. These instruments have common properties such as temporal resolution (repeat cycle), spectral resolution, spatial resolution (ground pixel size), and swath width. Of these, only the last two were considered to be potentially informative and thus were explored in this paper; the former were believed to have no relationship to CO_2 measurement accuracy though they may still be of interest for measuring CO_2. These properties are given as follows.

The orbital parameters of a satellite determine its *repeat cycle*, which is the time before the onboard instrument is able to image the same location in space. This repeat cycle can vary between 3 and 30 days. The time it takes before CO_2 concentration is determined within the same column of air should not have a relationship to the actual CO_2 concentration measured during a single measurement event. However, repeat cycle is important for annual estimates of CO_2 concentration, which are derived from more frequent measurements. The more frequent the measurement, the greater the probability that the emissions from episodic anthropogenic events such as startups, shutdowns, and malfunctions may be captured.

Spectral resolution is the smallest wavelength difference that an instrument can resolve. An instrument that can resolve wavelengths 0.25 nm apart is considered to have finer spectral resolution than one that can only resolve wavelengths 0.5 nm apart. Spectral resolution alone is not believed to have a good relationship to how well the instrument will measure CO_2 because coverage within the CO_2 absorption bands varies by instrument. An instrument might have fine spectral resolution within multiple bands because it was designed to sense a variety of atmospheric trace gases, whereas another instrument might have coarser spectral resolution but with greater coverage across one or more CO_2 absorption bands.

In contrast to temporal and spectral resolution, *spatial resolution* (ground pixel size) is believed to be more informative about CO_2 measurement accuracy. Studies that determine how accurate a satellite instrument is at detecting CO_2 do so by comparison to records obtained from the ground or from the air. These records are obtained locally, with a very fine spatial resolution. As the ground pixel size becomes smaller, the more the instrument's detected CO_2 will approximate the local CO_2 variations in such studies. When the instrument's spatial resolution and that of the ground records more closely match, the accuracy of the remotely sensed CO_2 emissions should increase.

Swath width is the width of the instrument's field of view, as projected onto the ground. A direct relationship between swath width and spatial resolution is expected because of limitations in the sensing technology used. An instrument with high spatial resolution will be more likely to have a narrow swath width because only so much light can be received by each element of the sensor. To achieve a wider swath width, the sensor would need to be larger, necessitating greater data processing and transfer requirements. Conversely, instruments designed to have a long swath width for broader land surface coverage should be expected to have coarser spatial resolution. Since spatial resolution is expected to have a relationship to CO_2 measurement accuracy, swath width is also expected to show a relationship.

Data and Methods

Instrument spatial resolution and swath width data was gathered from the ESA CEOS database, while a literature search was conducted for data on CO_2 measurement accuracy for those instruments (Table 1). Whenever two or more values were found for CO_2 measurement accuracy, the values were averaged. Next, exploratory plots were done with CO_2 measurement accuracy as the dependent variable and either spatial resolution or swath width as the independent variable. These plots suggested that one or more log transformations would be useful.

To further quantify the potential relationships between spatial resolution, swath width, and CO_2 measurement accuracy, multiple linear regressions were performed. This regression technique allows for the use of multiple independent variables as predictors within the same linear model, and also allows the fitting of linear interaction terms between one or more independent variables (Aiken *et al.* 1991).

Single-predictor models

Four regression models were fit for each of the two independent variables (Equations 1-4). These single-predictor models appear in the first eight rows of Table 2.

Equation (1) $Y = b_0 + b_1 X$
Equation (2) $Y = b_0 + b_1 \log X$
Equation (3) $\log Y = b_0 + b_1 X$
Equation (4) $\log Y = b_0 + b_1 \log X$

where
Y = CO2 measurement accuracy (ppmv) and
X = either spatial resolution (km^2) or swath width (km)

Two-predictor models

Next, models were fit with both independent variables as predictors to determine whether a better fit might be achieved.

Equation (5) $Y = b_0 + b_1 SR + b_2 SW$

where
Y = CO_2 measurement accuracy (ppmv) or its log transform
SR = spatial resolution (km^2)
SW = swath width (km)

Two-predictor models with an interaction term

Finally, models were fit with both independent variables as predictors, as well as an interaction term between spatial resolution and swath width.

Equation (6) $Y = b_0 + b_1 SR + b_2 SW + b_3 SR*SW$

where
Y = CO_2 measurement accuracy (ppmv) or its log transform
SR = spatial resolution (km^2)
SW = swath width (km)

The smallest value of Akaike's information criterion (AIC) was then used to determine the model with the best fit to the data (Burnham and Anderson 2002).

RESULTS

Single-predictor models

As was expected, CO_2 can be measured with greater accuracy when the spatial resolution (ground pixel size) of the satellite instrument becomes smaller (Figure 1). However, this relationship is weak; spatial resolution alone is not significant in three of the four models where it is the only factor (Table 2).

Swath width has a closer relationship to CO_2 accuracy than spatial resolution (Figure 2). As the swath width of the satellite instrument decreases, the instrument tends to be able to measure CO_2 with greater accuracy. The limit on CO_2 accuracy is the CO_2 LiDAR (ASCENDS); this laser-based instrument has the most narrow swath width of all, and can measure CO_2 to within 1 ppmv. In contrast to spatial resolution, swath width is significant in all four models where it appears as the only factor (Table 2).

Multiple-predictor models

In conducting exploratory plots of the data, a close relationship had been found between instrument spatial resolution and swath width (Figure 3). Finer spatial resolution is associated with a narrower swath width, as was originally expected because of constraints inherent in the spectrometer technology, constraints in data collection and transfer, or perhaps both.

To account for this relationship, models with an interaction term between spatial resolution and swath width were developed. These models perform better at fitting the data than those with single predictors, as well as a two-predictor model without this interaction term (Table 2).

The model of best fit in this analysis is Equation 7, with an AIC of -28.457. In this model, all three predictors are significant: spatial resolution, swath width, and an interaction term between spatial resolution and swath width.

Equation (7) $$\log(\mathrm{CO2Acc}) = 5.157\mathrm{e}{-02} + 5.800\mathrm{e}{-04}\ \mathrm{SR} + 3.347\mathrm{e}{-04}\ \mathrm{SW} - 5.912\mathrm{e}{-07}\ \mathrm{SR} * \mathrm{SW}$$

where

CO2Acc = CO_2 measurement accuracy (ppmv)
SR = spatial resolution (km^2)
SW = swath width (km)

The most accurate instruments

All instruments in this paper have sufficient sensitivity in one or more CO_2 absorption bands to detect CO_2 to within 4 ppmv of its ground or air-measured value (Table 1). However, only three instruments meet the spatial resolution and accuracy requirement posed by Bovensmann *et al.* (2010) for the monitoring of anthropogenic point sources. The CarbonSat mission planned for 2018 has an instrument with 2 ppmv accuracy and the largest spatial resolution of the three, at 2x2 km (4 km^2). The Tropospheric Emission Spectrometer (TES) currently in service has a 1.3 ppmv CO_2 measurement accuracy, and the second Orbiting Carbon Observatory (OCO-2) planned for 2013 is expected to have a 1 ppmv CO_2 accuracy. Following the general finding of this study that spatial resolution and swath width together are significant predictors of CO_2 measurement accuracy, these three instruments notably have the smallest swath widths of all the instruments examined (Figure 2). For the most accurate CO_2 emissions inventories obtained by remote sensing, data should be employed from the three instruments above.

CONCLUSIONS

The key finding of this study was the relationship of spatial resolution and swath width to CO_2 measurement accuracy. Spatial resolution alone is not significant but swath width is, and the combination of swath width and spatial resolution yields the best fit to the available data. This knowledge is important for the design of future CO_2-monitoring satellite instruments because of the increasing need for accurate estimates of anthropogenic CO_2 emissions.

If an instrument is to be designed to measure CO_2 concentration with the greatest accuracy, it should ideally be designed with a fine spatial resolution of 2x2 km (4 km^2) or less, and the smaller the swath width the better, up to an extent. As swath width decreases, the time it takes to acquire complete coverage of an area increases. As spatial resolution becomes finer, the amount of data from the instrument that must be transmitted and processed also increases. Thus, the best solution would be an instrument with the requisite 4 km^2 or less spatial resolution, and as broad a swath width as possible without sacrificing measurement accuracy. The CarbonSat instrument meets both these criteria, but unfortunately will not be launched before 2018.

It should be noted that measuring CO_2 concentration is only the first step in determining the anthropogenic CO_2 fluxes that are the actual emissions into the atmosphere by human activities (JASON 2011). A necessary next step in the process is the "model inversion" required to go from concentration measurements to emissions estimates. Since the transport of CO_2 from source to point of measurement is highly dependent on meteorological variables such as wind speed and temperature, the modeling uncertainty may very well dominate measurement uncertainty.

However, progress has been made in lowering the modeling uncertainty. A high-resolution (1.3 km) mesoscale atmospheric transport model was recently coupled with ground-based observations to detect a change in emissions of approximately 15% at the 95% confidence level (McKain *et al.* 2012). Though ground-based observations were used, the authors of this study argue that more precise urban emissions estimates should be obtainable using integrated column CO_2 measurements from the ground and/or space, due to having lower sensitivity than surface point measurements to the redistribution of emitted CO_2 by small-scale processes.

If modeling uncertainty can be significantly lowered, then advances in the accuracy of measuring CO_2 concentration from space will have a greater impact on increasing the accuracy of CO_2 emissions estimates. A study by the JASON scientific advisory group (2011) determined that a CO_2 measurement uncertainty of +/- 20% (90% confidence level) was possible if a combination of satellite observations, accurate meteorological data, and a ground sensor network was used. Thus, CO_2 emissions inventories conducted entirely by remote sensing should employ additional data sources from the ground in order to boost the measurement accuracy. Likewise, existing ground-based emissions inventories will benefit from using remotely sensed CO_2 emissions data. As examples, the ODIAC CO_2 emissions inventory used remotely sensed night light data as a proxy for CO_2 emissions sources, combined with ground-measured emissions data to enhance the inventory (Oda and Maksyutov 2011). The comprehensive Vulcan CO_2 inventory offers spatial scales as small as 10x10 km and time scales as small as hours, but unfortunately was done without the incorporation of any remotely sensed data. Further improvements in the accuracy of CO_2 emissions inventories are yet to come, in the form of products that merge both the remote sensing and ground-based approaches.

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KEY WORDS

CO_2 remote sensing, anthropogenic CO_2 emissions, satellite instruments

Table 1. Properties of CO_2-sensing satellite instruments.

Mission Name Short	Launch Date	EOL Date	Mission Instruments	Instrument Name	Spectral Ranges	CO2 accuracy (average ppmv)	Spatial Resolution (km^2)	Swath Width (km)
NOAA-15	1-May-98	31-Dec-11	HIRS/3	High Resolution Infrared Sounder/3	0.69-14.95 um	4 (Dolman 2011)	412.09	2240
NOAA-16	21-Sep-00	31-Dec-12	HIRS/3	High Resolution Infrared Sounder/3	0.69-14.95 um	4 (Dolman 2011)	412.09	2240
Envisat	1-Mar-02	31-Dec-13	MIPAS	Michelson Interferometric Passive Atmosphere Sounder	4.15-14.6 um	n/a	90	30
			SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography	240 - 314 nm, 309 - 405 nm, 394 - 620 nm, 604 - 805 nm, 785 - 1050 nm, 1-1.75 um, 1.94-2.04 um and 2.265-2.380 um	2.5 (Reuter et al 2011)	1800	1000
Aqua	4-May-02	30-Sep-13	AIRS	Atmospheric Infra-red Sounder	4-10 um and 3.7-15.4 um	1.8 (Maddy et al 2008) 1.5 (Dolman 2011)	182.25	1650
NOAA-17	24-Jun-02	31-Dec-14	HIRS/3	High Resolution Infrared Sounder/3	0.69-14.95 um	4 (Dolman 2011)	412.09	2240
SCISAT-1	12-Aug-03	1-Mar-14	ACE-FTS	Atmospheric Chemistry Experiment (ACE) Fourier Transform Spectrometer	2-13 um (750-4500 cm-1)	2 (Foucher et al 2009)	n/a	solar occultation
Aura	15-Jul-04	30-Sep-13	TES	Tropospheric Emission Spectrometer	3.2-15.4 um	1.3 (Dolman 2011)	2.809	18
NOAA-18	20-May-05	31-Dec-15	HIRS/4	High Resolution Infrared Sounder/4	0.69 um, 3.7-4.6 um, 6.7-15 um	4 (Dolman 2011)	314.16	2240
Metop-A	19-Oct-06	31-Dec-13	HIRS/4	High Resolution Infrared Sounder/4	0.69 um, 3.7-4.6 um, 6.7-15 um	4 (Dolman 2011)	314.16	2240
			IASI	Infrared Atmospheric Sounding Interferometer	3.4-15.5 um with gaps at 5 um and 9 um	2 (Crevoisier et al. 2009) 2 (Dolman 2011)	625	2052
FY-3A	27-May-08	31-Dec-11	IRAS	Infrared Atmospheric Sounder	0.65-14.95 um	2 (Dolman 2011)	196	952
GOSAT	23-Jan-09	22-Jan-14	TANSO-FTS	Thermal and Near infrared Sensor for carbon Observation – Fourier Transform Spectrometer	0.758-0.775 um (O2), 1.56-1.72 (CO2-CH4), 1.92-2.08 (CO2-H2O), 5.56-14.3 (CO2-CH4)	2.8 (Butz et al. 2011) 4 (Dolman 2011)	110.25	750

Mission Name Short	Launch Date	EOL Date	Mission Instruments	Instrument Name	Spectral Ranges	CO2 accuracy (average ppmv)	Spatial Resolution (km^2)	Swath Width (km)
NOAA-19	4-Feb-09	1-Mar-16	HIRS/4	High Resolution Infrared Sounder/4	0.69 um, 3.7-4.6 um, 6.7-15 um	4 (Dolman 2011)	314.16	2240
FY-3B	5-Nov-10	31-Dec-13	IRAS	Infrared Atmospheric Sounder	0.65-14.95 um	2 (Dolman 2011)	196	952
NPP	28-Oct-11	25-Aug-16	CrIS	Cross-track Infrared Sounder	3.92-4.4 um, 5.7-8.62 um, 9.1-14.7 um	2 (Dolman 2011)	615.75	2200
Metop-B	31-May-12	31-May-17	HIRS/4	High Resolution Infrared Sounder/4	0.69 um, 3.7-4.6 um, 6.7-15 um	4 (Dolman 2011)	314.16	2240
			IASI	Infrared Atmospheric Sounding Interferometer	3.4-15.5 um with gaps at 5 um and 9 um	2 (Crevoisier et al. 2009) 2 (Dolman 2011)	625	2052
MIOSAT	1-Apr-13	1-Apr-15	--	Mach-Zehnder Micro-Interferometer	0.4 - 4.5 um	n/a	25	5
Environsat-1	1-Dec-13	1-Dec-17	HRSS-1	High Resolution SWIR Spectrometer	1.575-1.625 um	n/a	--	380
OCO-2	15-Dec-13	15-Dec-16	OCO-2	Orbiting Carbon Observatory-2	0.758-0.772 nm (O2), 1.594-1.619 (CO2), 2.042-2.082 (CO2)	1 (Dolman 2011)	2.9025	10.3
FY-3C	31-Dec-13	31-Dec-16	IRAS	Infrared Atmospheric Sounder	0.65-14.95 um	2 (Dolman 2011)	196	952
Metop-C	2-Apr-16	1-Dec-21	IASI	Infrared Atmospheric Sounding Interferometer	3.4-15.5 um with gaps at 5 um and 9 um	2 (Crevoisier et al. 2009) 2 (Dolman 2011)	625	2052
Environsat-2	1-Dec-16	1-Dec-20	HRSS-1	High Resolution SWIR Spectrometer	1.575-1.625 um	n/a	--	380
JPSS-1	1-Jul-17	1-Jun-23	CrIS	Cross-track Infrared Sounder	3.92-4.4 um, 5.7-8.62 um, 9.1-14.7 um	2 (Dolman 2011)	615.75	2200
ASCENDS	1-Sep-20	1-Jan-23	CO2 LIDAR (ASCENDS)	CO2 LIDAR (ASCENDS)	1.57233 um	1 (Dolman 2011)	~1e-6	0.2
JPSS-2	1-Jan-23	1-Oct-29	CrIS	Cross-track Infrared Sounder	3.92-4.4 um, 5.7-8.62 um, 9.1-14.7 um	2 (Dolman 2011)	615.75	2200
CarbonSat	2018	--	CarbonSat	CarbonSat	0.757-0.775 um, 1.559-1.675, 2.043-2.095	2 (Dolman 2011)	4	500

Table 2. Details of the linear models tested.

Single Predictor

y-variable	x-variable	intercept	significance	slope	significance	Model AIC
log CO2Acc	log SpatRes	0.11846	0.2857	0.11634	0.0169 *	-14.754
CO2Acc	log SpatRes	1.3929	0.0515 .	0.5383	0.0672 .	65.733
log CO2Acc	SpatRes	3.616e-01	3.83e-06 ***	5.967e-05	0.575	-8.6787
CO2Acc	SpatRes	2.5804261	2.53e-07 ***	0.0001213	0.847	69.468
log CO2Acc	log SwathWidth	-0.01689	0.854205	0.13504	0.000201 ***	-21.058
CO2Acc	log SwathWidth	0.8080	0.18407	0.6128	0.00489 **	64.899
log CO2Acc	SwathWidth	1.280e-01	0.05448 .	1.573e-04	0.00028 ***	-20.368
CO2Acc	SwathWidth	1.3183768	0.00216 **	0.0008100	0.00123 **	62.063

Two Predictors

CO2Acc ~ SpatRes + SwathWidth	61.69

```
               Estimate Std. Error t value Pr(>|t|)
(Intercept)  1.4650858  0.4412987   3.320  0.00360 **
SpatRes     -0.0004298  0.0005359  -0.802  0.43239
SwathWidth   0.0008361  0.0002564   3.261  0.00411 **
```

log(CO2Acc) ~ log(SpatRes) + log(SwathWidth)	-19.308

```
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)        -0.21401    0.16086  -1.330   0.1991
log10(SpatRes)     -0.05640    0.07799  -0.723   0.4784
log10(SwathWidth)   0.24158    0.09408   2.568   0.0188 *
```

Two Predictors + Interaction

CO2Acc ~ SpatRes * SwathWidth	52.536

```
                     Estimate  Std. Error t value Pr(>|t|)
(Intercept)          8.164e-01  3.990e-01   2.046  0.05564 .
SpatRes              3.105e-03  1.111e-03   2.795  0.01196 *
SwathWidth           1.908e-03  3.721e-04   5.127 7.05e-05 ***
SpatRes:SwathWidth -3.383e-06  9.814e-07  -3.448  0.00287 **
```

log10(CO2Acc) ~ log10(SpatRes) * log10(SwathWidth)	-17.435

```
                     Estimate Std. Error t value Pr(>|t|)
(Intercept)          -0.14759    0.26361  -0.560   0.5825
log10(SR)            -0.16004    0.33087  -0.484   0.6344
log10(SW)             0.21692    0.12299   1.764   0.0947 .
log10(SR):log10(SW)  0.03351    0.10383   0.323   0.7506
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log10(CO2Acc) ~ SpatRes * SwathWidth	-28.457

```
                      Estimate Std. Error t value Pr(>|t|)
(Intercept)          5.157e-02  6.332e-02   0.814  0.42603
SpatRes              5.800e-04  1.763e-04   3.291  0.00406 **
SwathWidth           3.347e-04  5.905e-05   5.668 2.24e-05 ***
SpatRes:SwathWidth -5.912e-07  1.558e-07  -3.796  0.00132 **
```

```
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Figure 1. CO_2 measurement accuracy and spatial resolution of CO_2-sensing satellites.

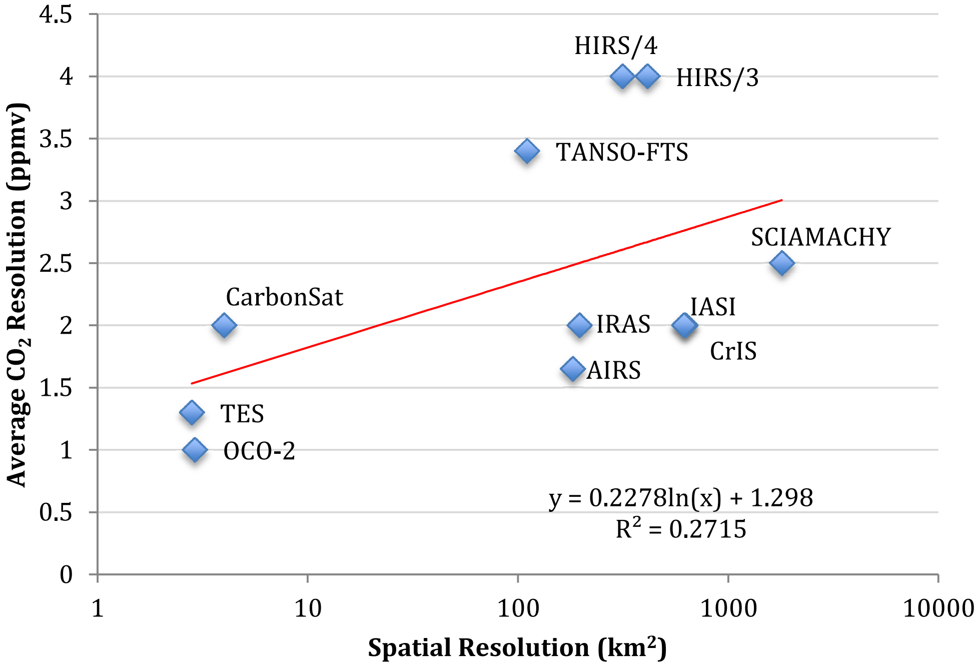

Figure 2. CO_2 measurement accuracy and swath width of CO_2-sensing satellites.

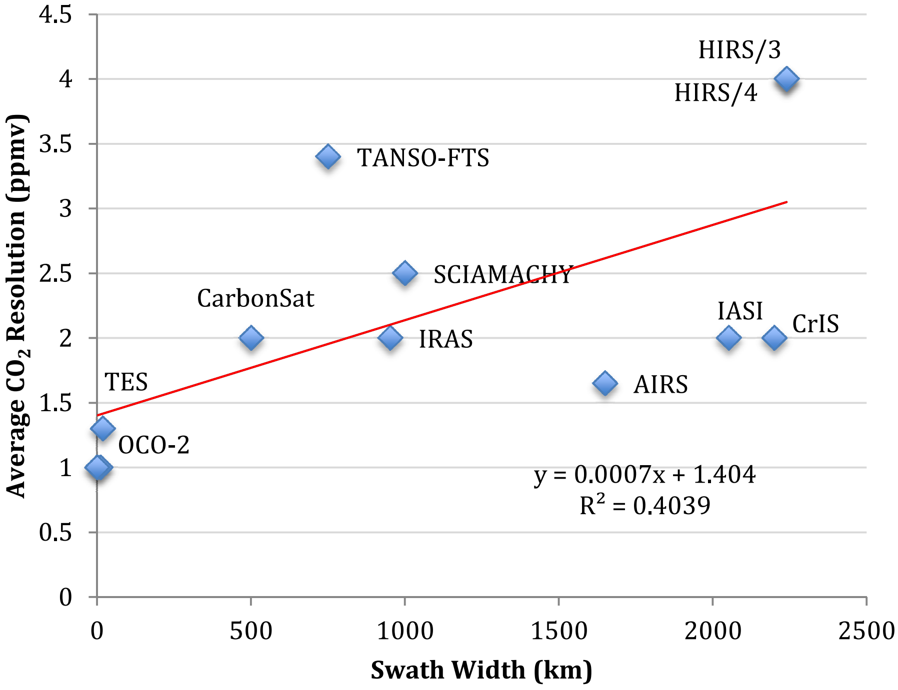

Figure 3. Variation of instrument spatial resolution with swath width.