P1.17 VALIDATION OF GOES IMAGER EXPERIMENTAL LOW CLOUD DATA PRODUCTS FOR TERRESTRIAL FREE SPACE OPTICAL TELECOMMUNICATIONS

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1. INTRODUCTION

Free Space Optical (FSO) telecommunications refers to the transmission of optical signals through free space or air. FSO can be used to communicate voice, video, and data through the atmosphere using lasers. FSO communication provides a practical alternative to fiber-optic communication; however, the atmosphere is a less-predictable medium than fiber-optic cable. Fog particles in the atmosphere have radii similar to FSO wavelengths (Willebrand and Ghuman, 2002) and can attenuate or obstruct the passage of optical signals. Although other atmospheric conditions such as rain and snow can affect system performance, the impact of fog is much more detrimental. Fog and low clouds are the most challenging and unpredictable environmental obstacles in developing reliable FSO networks.

In order to better map local effects of fog, Terabeam has been evaluating the use of satellite imagery including Landsat (Fischer *et al*., 2001) and, more recently, the *GOES Low Cloud Base (LCB)* data product developed by NOAA/NESDIS (Ellrod, 1995; Ellrod, 2002). This study shows a preliminary comparison of cloud ceiling data from the *GOES LCB* product and ceilometer data up to 25,000 ft as well as *in situ* visibility data at three different elevations below 1000 ft in San Francisco, CA. One of the challenges of this comparison has been the highly localized meteorology of the San Francisco Bay area combined with the relative coarseness of the GOES pixels.

1.1 Background on Satellite Imagery and Fog

Satellite imagery has been useful for quite some time in the detection of fog and low stratus. It is only fairly recently, however, that satellite imagery has been used to determine more detailed properties of fog and low-based clouds. Bendix (2001) prepared a preliminary fog climatology of Europe using NOAA-AVHRR data, calculating optical depth τ, Liquid Water Path (LWP) and effective drop size radius, r_e. Fog occurrence was mapped from its highest in pre-alpine regions to its lowest in the inland transition zones between the maritime coastal and pre-alpine regions. The satellite-based fog climatology was able to replicate the dense Po river valley fog which had an average $\tau > 12$, a high LWP and an r_e of ~6.7 µm. This was in contrast to Adriatic coastal fog where the LWP decreases but r_e increased to ~8 µm and τ decreased to <6. Gurka (2001) sees increasing usefulness in the next generation GOES for use in improving cloud ceiling and visibility forecasts. Despite its current relatively low vertical and horizontal resolution, GOES provides excellent temporal resolution. The next generation GOES should display a significant improvement in its horizontal and vertical resolution.

2. INSTRUMENTS AND DATA

2.1 GOES Experimental Low Cloud Base Product

The *GOES LCB* product uses surface temperatures from *Met*eorological *A*viation *R*eporting (METAR) stations in combination with GOES 10.7 µm Infrared (IR) cloud top temperatures. If differences between the surface temperature and the 10.7 µm IR channel are = 3 K or less, cloud base heights are classified as <1000 feet Above Ground Level (AGL), known in aviation as *Instrument Flight Rule (IFR)* ceilings (see Figure 1). This algorithm is based on a vertical temperature profile associated with low stratus cloud formation in which a thermal inversion exists above a well-mixed layer. Under these conditions, the GOES IR observes the top of the stratus cloud, where the IR temperature is usually warmer than the inversion base, and possibly the surface also. The closer the cloud top temperature (CTT) is to the surface temperature (T_{sfc}), the smaller their difference, and the more likely IFR ceilings are to exist. In addition to detecting IFR ceilings, the LCB product also displays non-IFR ceilings and cirrus. Imagery is produced hourly during the night from GOES-8 and GOES-10 satellite data, on national, regional, and metropolitan scales.

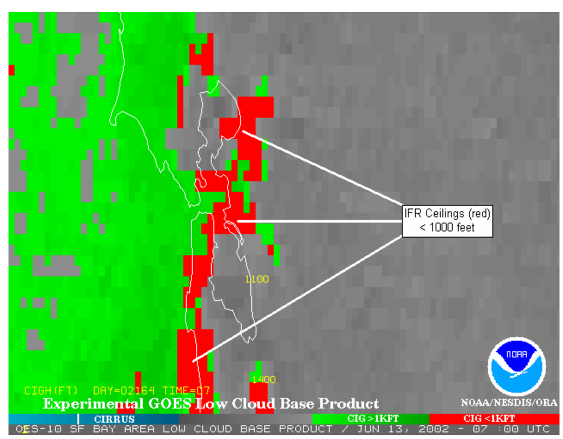

Figure 1. GOES Low Cloud Base image of San Francisco/Sacramento metropolitan area from June 13, 2002 at 0700 UTC (0000 PDT).

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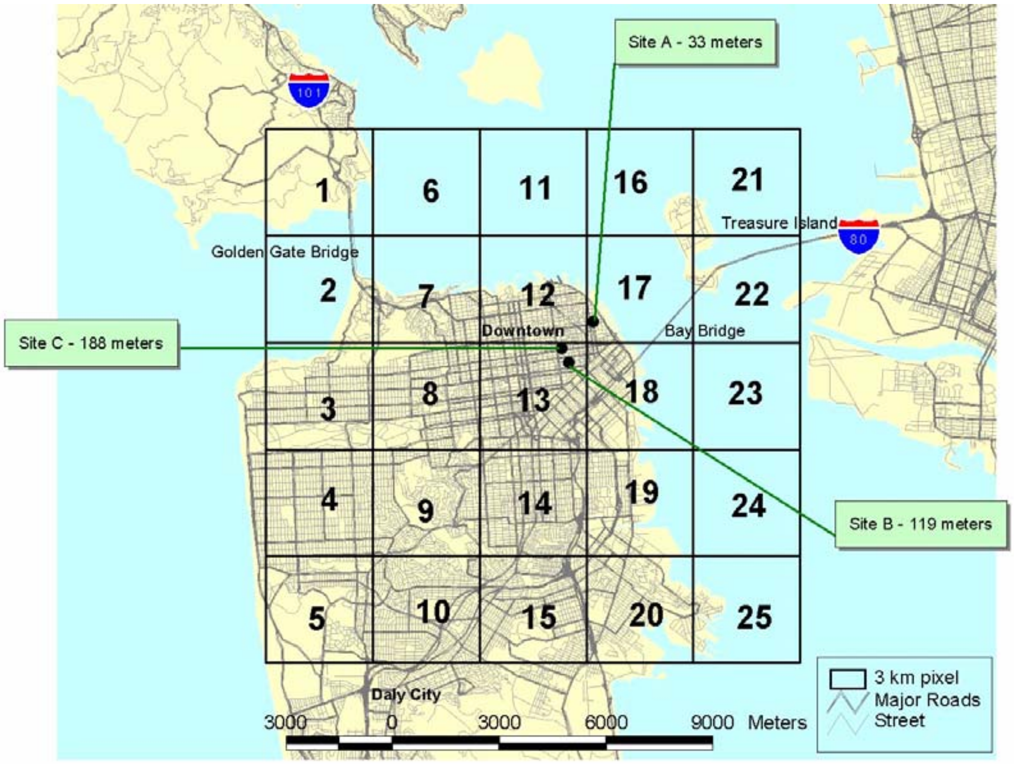

Figure 2. Map of San Francisco area displaying both Terabeam weather network and location of ground cells corresponding to GOES LCB pixel grid.

2.2 Terabeam Weather Network in San Francisco

In spring 2001, Terabeam deployed a network of weather instruments in San Francisco to take advantage of the foggy weather and hilly terrain to study optical properties of fog and low clouds. The network is located on the northeastern tip of the San Francisco peninsula. The instruments include three visibility sensors at different elevations, one ceilometer, and one weather station (see Table 1 and Figure 2). The ceilometer detects up to three cloud ceiling levels. For this study, the ceilometer and visibility sensors were used as validation tools for the GOES LCB product.

3. ANALYSIS AND RESULTS

Cloud ceiling height measurements from the ceilometer at Site A were compared with pixel brightness count values from the LCB product. The brightness counts are based on an 8-bit (256 value) scale ranging from 0 to 255. NOAA/NESDIS has interpreted this scale into four ceiling types: IFR ceilings, non-IFR ceilings, no clouds, and cirrus. From these interpretations, four satellite categories were created and ceilometer data was categorized accordingly.

Using this categorization, a 5 x 5 grid of LCB pixels (see Figure 2) were analyzed and compared with ceilometer values. The grid covers an area approximately 15 x 15 km centered on downtown San Francisco (37.78° N, 122.42° W). GOES nighttime navigation can be off by several kilometers and has an official navigation specification of *< 6 km, 99% of the time*. A large grid was used to take the navigation specification into account.

Site	AMSL (m)	Meas.	Sensor	Accuracy Range
Site A	33 m	Cloud Ceiling	Vaisala CT25K	0 - 7500 m (ht.range)
		Visibility	Qualimetrics 8364	10 - 32000 m
Site B	119 m	Visibility	Belfort Model 6100	6 - 16000 m
Site C	188 m	Visibility	Belfort Model 6100	6 - 16000 m

Table 1. Ceilometer and visibility sensors in San Francisco. Elevations expressed as equipment height above mean sea level (AMSL).

Category	LCB Brightness Count	LCB Interpretation	Ceilometer Data
1	200-255	IFR Ceiling (< 1000 ft)	< 305 m
2	141-199	Non-IFR Ceiling	305 – 6000 m
3	79-140	No Clouds	Non-reported
4	0-78	Cirrus	> 6000 m

Table 2. Categories created to compare satellite data with ceilometer data.

3.1 *Ceilometer Analysis*

The LCB product is created once per hour from 3 – 12 UTC (7 PM – 4 AM PST). The brightness counts from this hourly data were categorized for the six month time period of February 6 - August 6, 2002. In total, 1766 pixel grids (and corresponding ceilometer data) from the six month period were categorized. There were some missing data between 4 – 7 UTC due to springtime satellite "eclipse".

In Tables 3 (a-d), LCB categories were compared with ceilometer categories and inspected for agreement or non-agreement status. When satellite data were classified as Category 1, agreement status was achieved if *one* or more of the three ceilometer ceiling height measurements was also Category 1. The same method was used for Categories 2 and 4; however, for Category 3, agreement status was only achieved if *no* clouds were reported at any height by the ceilometer. Figure 3 shows a graphical comparison of satellite brightness and ceilometer heights.

Category 1 (IFR ceilings) had the highest percentage of agreement, with a 25 pixel average of about 76%, including nine pixels with >80% agreement percentages. Category 3 (no clouds) also had a promising agreement percentage of about 73% on average. Categories 2 (non-IFR ceilings) and 4 (cirrus) had lower agreement percentages, averaging around 39% and 22%, respectively.

There are some obvious reasons that account for less than perfect agreement percentages in all four categories. The navigation specification of the satellite image did not ensure that pixel data being compared actually referred to the correct ground cell. Also, pixels up to 9 km from the ceilometer location (not taking the navigation specification into account) were compared to ceilometer measurements. The coarse resolution of the LCB product is also a factor in lowering agreement percentages. The LCB algorithm assigns a ceiling cover value to a 3 x 3 km ground cell, while there could be different ceiling types occurring simultaneously within the cell.

Some disagreement in Category 1 was likely due to cloud layer formation within thermal inversions at altitudes greater than 1000 feet AGL. In these non-IFR inversion cases, the IR cloud top temperature component of the LCB algorithm is given a high temperature value, falsely indicating IFR ceilings. These disagreement cases, referred to as *false alarms*, were not widespread. This is portrayed by the Category 1 agreement percentages, which were mostly between 70-90%.

73.1	74.3	74.7	***81.1***	***85.1***
68.8	69.2	73.6	***84.8***	***85.5***
67.2	72.7	76.9	***86.3***	***85.9***
69.8	65.2	66.9	77.8	***85.5***
70.9	65.8	71.0	***88.8***	***85.9***

(a) Category 1 (IFR Ceilings)

38.8	39.3	***41.1***	***42.0***	***41.7***
35.9	36.1	39.1	***40.9***	***40.5***
36.3	38.9	***40.3***	***40.8***	***42.3***
34.8	37.0	37.0	38.4	37.1
36.2	37.5	37.9	39.9	***40.1***

(b) Category 2 (Non-IFR Ceilings)

72.9	72.0	70.7	70.9	72.0
73.4	73.4	***74.4***	***75.1***	***74.0***
73.6	***74.9***	***75.2***	***75.1***	73.7
73.5	73.5	73.5	73.0	69.5
73.6	***74.0***	73.6	71.0	69.4

(c) Category 3 (No Clouds)

20.8	22.2	***23.0***	22.2	21.6
21.7	***23.5***	20.5	21.0	21.8
20.7	21.3	21.1	21.5	22.0
20.4	20.5	22.4	***24.4***	22.1
24.0	***24.2***	***24.0***	***23.3***	***24.9***

(d) Category 4 (Cirrus)

Tables 3 (a-d). Pixel grids for each brightness value category. Numbers give percentage of occurrences that ceilometer data agreed with brightness value category. Highest percentages in bold. Refer to Figure 2 for grid orientation.

In Category 2, disagreement occurred more often. Most of the time, this was probably due to multiple-layered cloud conditions and thin cirrus. In such conditions, it's possible that non-IFR ceilings were detected by the LCB product, while IFR ceilings existed below. Similarly, for Category 4, IFR and/or non-IFR ceilings may have often been obscured by the cirrus above. These disagreement cases are referred to as *under-detection*. Category 4 agreement percentages also suffered due to the fact that any cirrus above 7.5 km was not in the ceilometer detection range.

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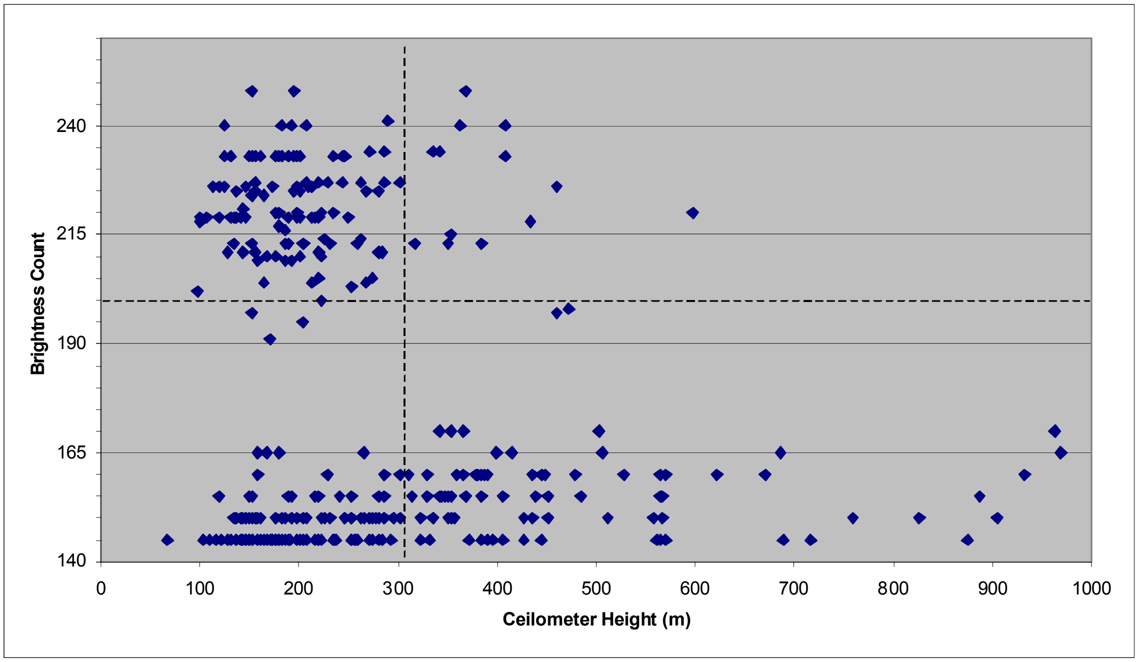

Figure 3. Pixel 17 brightness values plotted against ceilometer ceiling heights. Top-left and bottom-right quadrants (separated by dashed lines) show category 1 and 2 agreement, respectively. Top-right shows false alarms, bottom-left shows under-detection.

The highest Category 1 agreement percentages were on the eastern portion of the pixel grid, overlying San Francisco Bay and part of downtown San Francisco. The slightly lower agreement percentages to the west suggest a possible urban heat island influence on the LCB algorithm. Higher surface temperatures over the city could have decreased the amount of IFR ceilings detected in the LCB algorithm, resulting in under-detection. Although the exact location of all METAR stations used is not known, proximity of these stations to the urban heat island or water could affect detection of IFR ceilings. For instance, lower temperatures at San Francisco International Airport (SFO), an area less affected by urban heat than other parts of the city, could explain the higher agreement percentages over San Francisco Bay. The easterly/northeasterly trend in Categories 1 and 2 agreement percentages also suggest a potential systematic trend for the GOES navigation specification.

3.2 Visibility Analysis

Visibility sensor data was compared with pixel brightness count values for the same six month period as the ceilometer data (February 6 – August 6, 2002). Visibilities were examined when both the LCB product and ceilometer agreed on Category 1, and furthermore when ceilometer ceiling height measurements were equal to or below visibility sensor elevations. This improved the viability of the visibility data being examined by increasing the chance that the visibility sensors were actually within fog or low cloud. Visibility data under these circumstances was limited. Ceilometer ceiling heights were rarely below the Site B sensor and never below the Site A sensor. The latter being due to the fact that the ceilometer is at the same height as the Site A visibility sensor.

Site C data was analyzed for visibility occurrences below or equal to 1600 m, 800 m, and 400 m (see Table 4). This required the ceilometer heights to be less than or equal the height of the Site C sensor (188 m AMSL). For a 25 pixel average, visibilities were 1600 m or less 87% of the time, 800 m or less 62% of the time, and 400 m or less 37% of the time. Figure 4 shows a histogram and cumulative distribution for visibilities observed at the Site C when pixel was Category 1.

Pixel	Visibility = 1600 m	Visibility = 800 m	Visibility = 400 m
8	90.4%	63.5%	40.4%
13	86.5%	61.5%	38.5%
17	88.0%	64.0%	36.0%

Table 4. Percentages that Site C visibilities were below certain thresholds. For this comparison, brightness values at the selected pixels had to be Category 1 and ceilometer ceiling heights lower than the Site C sensor height (188 m).

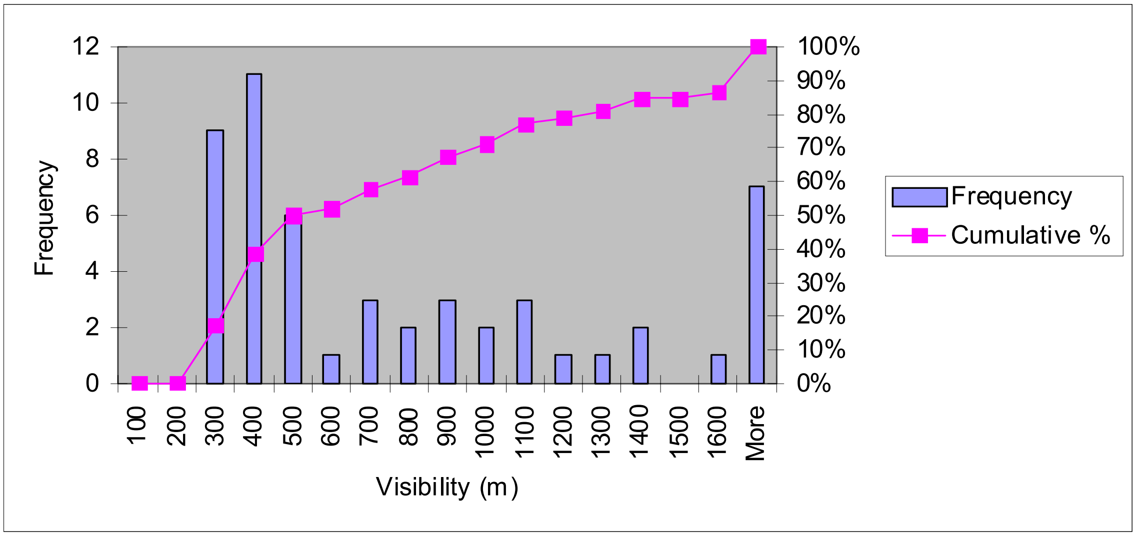

Figure 4. Histogram for visibility occurrences at Site C when satellite data at pixel 13 was Category 1 and ceilometer ceiling heights were below elevation of the Site C sensor.

4. CONCLUSION

When the GOES LCB product detected IFR ceilings, this gave a fairly reliable indication that IFR ceilings were present in downtown San Francisco. High reliabilities (near 90%) occurred for LCB pixels over the eastern side of the city and San Francisco Bay, likely due to close proximity to the ceilometer site, favorable location of the weather stations used to obtain surface temperatures, and limited urban heat island effect. When the LCB product detected non-IFR ceilings, the ceilometer often measured IFR ceilings. Under-detection occurred more frequently than false alarms.

When the LCB product and ceilometer both agreed on the presence of IFR ceilings, visibilities at Site C were below 1 mile (1600 m) between 80-90% of the time, depending on the LCB pixel being compared.

The GOES Low Cloud Base product proves to be an important resource for FSO atmospheric studies. In terms of future work, analysis of longer time series, preferably including fall and winter months, would be beneficial. The winter climate in San Francisco often exhibits visibilities and cloud ceilings much lower than those observed in the summer (Al-Habash et al., 2002). The lower cloud ceilings in particular would lead to improved visibility analysis, as ceiling heights would occur below visibility sensor heights more frequently. Also, comparisons could be made with other fog products developed by NOAA/NESDIS, such as the Fog Product and the Fog Depth Product.

5. REFERENCES

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