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VBFRED-IVY: THE DEVELOPMENT OF A COMPUTATIONAL TOOL TO MODEL THE THERMAL PERFORMANCE OF PLANTS ON BUILDINGS IN THE SINGAPORE CLIMATE

HONG YAN, BOON LAY ONG AND GUAN TIONG LIM
National University of Singapore
Singapore

Abstract. This paper reports the development of VBFRED-IVY, a computational tool that is used to model and analyze the thermal effects of plants on buildings under Singapore climatic conditions. In VBFRED-IVY, the vegetation-air temperature and surface temperature of a planted wall and a non-planted wall are investigated respectively. Climatic data of Singapore are input to do the parametric testing. Then field measurements are carried on three planted walls in different orientations, and statistics method is applied to evaluate the simulation program. The results show that VBFRED-IVY is efficient.

1. Introduction

In hot-humid tropics where Singapore is located, the thermal environments of buildings are much warmer than their surrounds primarily due to the solar radiation gained by the buildings in the daytime. However, when plants are used on the building, far less incoming solar energy reaches the building mainly because of the shade from the plant. In addition, the evaporation of water through transpiration results in lower temperature and higher humidity.

Parker (1980) found that “although using vegetation to cool a residence is not a new concept, many recent attempts to build energy-efficient buildings have totally ignored its significance: the primary reason for this omission is the lack of detailed quantitative data as to how effective vegetation is in reducing the energy used in heating and cooling a residence.” This is also the case in Singapore. Although Singapore is heavily landscaped, little of the planting is used to shade buildings to save cooling energy. One important reason of this situation is the shortage of detailed quantitative data to illustrate the effectiveness of plants in reducing cooling energy in local buildings.

Although computer models developed to simulating the cooling energy saving by vegetation were relatively well explored (Holm, 1989; Akbari et al., 1997), computer model for simulating the outside surface temperature reduction by vegetation in Singapore climate is less advanced investigated.

2. History

VBFRED-IVY is a computer simulation program written in Visual Basic based on FRED-IVY (23 May 1995), which is based upon FRED-AIR (FRED12P – 17 FEB 1992). FRED-AIR was an hourly simulation model and originally developed by Dr. Nick Baker (Baker, 1985) of the Martin Centre to study passive solar gains in buildings, and FRED-IVY was originally developed and written in QBasic by Dr. Boon Lay Ong to calculate the thermal behavior of the creeper on a south-facing wall (Ong, 1996).

In FRED-IVY, the plant thermal exchanges were calculated in a subprogram called FOLIAGE within the main energy section using an algebraic solution. There were four primary thermal nodes to be considered in FOLIAGE: the creeper, the air bound within the foliage, the external air and the wall which was further subdivided into 7 nodes to better represent the flow of heat through (Figure 1). The wall was assumed to be connected to an internal space, which was regarded as a heat sink maintained at a constant arbitrary temperature at 20 ^{o}C (Ong, 1996).

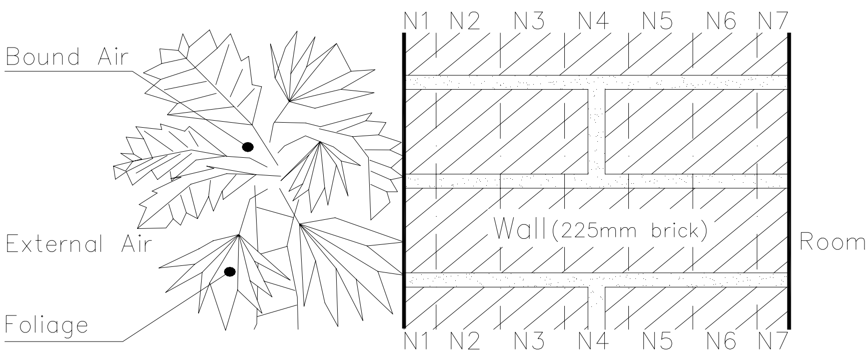


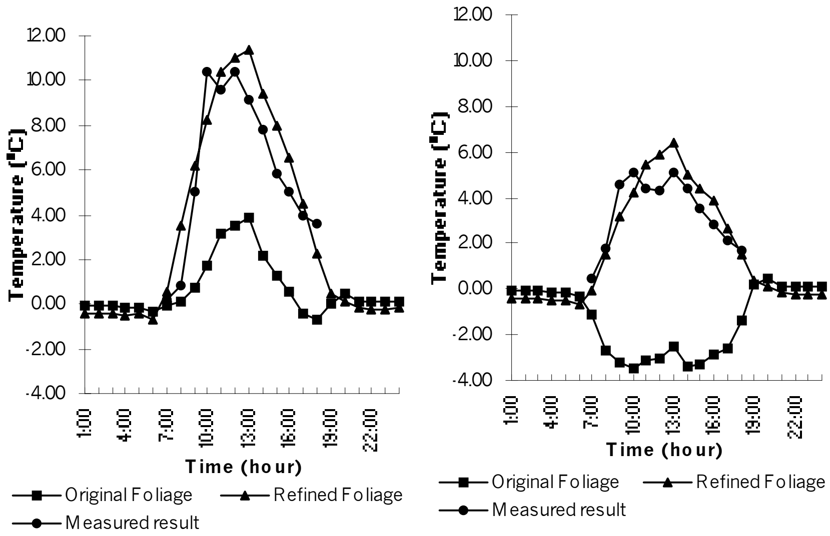
Figure 1. Thermal nodes for a creeper on an external wall.

3. Refinement and Development

VBFRED-IVY is developed by authors by conversing FRED-IVY from the QBasic to Visual Basic, and further developed by refining FOLIAGE and adding new subprograms to model the thermal performance of plants on a wall under various wall orientations, wall constructions, and wall's surface reflectivity in different seasons and dates of year under Singapore climatic condition. In VBFRED-IVY, a friendly input and output interface is also created for easy use.

3.1 REFINEMENT

According to the theoretical bases of FOLIAGE: energy balance of energy exchanges occurring in the plants, refinements are made in FOLIAGE to make it more accurate and appropriate for Singapore situation (Figure 2).



a. Dark color wall (surface reflectivity= 0.3) *b. Light color wall (surface reflectivity =0.7)*

Figure 2. Comparisons of thermal effects of plants in reducing wall surface temperature predicted by original and refined Foliage, and measured result on south facing walls in December in Singapore.

After comparing the results predicted by refined FOLIAGE and original FOLIAGE, we find that the results predicted by refined FOLIAGE are more approximating the real thermal effect of plants on local buildings. Thus the refinements are considered to be satisfactory.

3.2 DEVELOPMENT

VBFRED-IVY is further developed by adding new subprograms to model the thermal performance of plants on a wall under Singapore climatic condition. The effects of six factors are taken into consideration in this further development: density of plant cover, seasons and dates of year, air movement, surface reflectivity, orientation and construction of a wall.

3.2.1 Local Climatic and Building Conditions

Local climatic data are collected from S. P. Rao (Rao, 1994), M. B. Ullah (Ullah, 1993), and Singapore Meteorological Service (Singapore Meteorological Service, 1996). Local building data, mainly the typical wall constructions are collected from K. R. Rao and Hooi Choo Tan (Rao and Tan, 1977). The collected climatic and building data are analyzed and calculated by authors to constitute the data sources of VBFRED-IVY.

3.2.2 New Subprograms

In the equation (1) to calculate the net direct radiant solar energy flux absorbed by plants, there is a sun angle correction, cosθ, which is an application of Lambert's Cosine Law (Ong, 1996). θ is the angle between the beam and the normal to the surface (Jones, 1992, p.15), so θ is the angle of incidence.

$$I_{dir,L} = \alpha_L I_{H,r} \{1 - e^{-kL/\cos\theta} [1 - r_W (1 - e^{-2kL})]\} \ Wm^{-2} \quad (1)$$

To investigate thermal performance of plants on local buildings, it is significant to know the cosθ for different wall orientations of every hour in Singapore. A new subprogram called SunIncidencdAngle to calculate cosθ is developed and written in Visual Basic based on equations (2) (Markus, 1980, p.172) and added by authors in VBFRED-IVY.

$$\cos\theta = \cos\beta \cos\gamma \quad (2)$$

where θ = Incidence of angle on a vertical surface
β = Solar altitude
γ = Wall solar azimuth of a vertical surface

Other main new subprograms developed and added by authors in VBFRED-IVY include subprogram WebBulbTemperature for conversing relative humidity to web bulb temperature, subprogram ShowGraphic which has a series subprograms for showing results by drawing figures, and so on.

3.3 INPUT AND OUTPUT INTERFACE

In VBFRED-IVY, a friendly input and output interface just like the interface of Windows operational systems is designed: user can select diverse climatic and building conditions simply by clicking the buttons. Final results are shown in table and figure that can be easily understood. To use VEFRED-IVY, users do not have to understand the code of this simulation program, neither to know the program language of Visual Basic. This advantage can let more researchers to make use of VBFRED-IVY without any difficulty. Following are the main process of using VBFRED-IVY (Figure 3).

1) Select a climatic and a wall data
2) Select a planted wall or non-planted wall, for a planted wall, input leaf area index (LAI)
3) Select simple or detail result, then click Start Simulation button

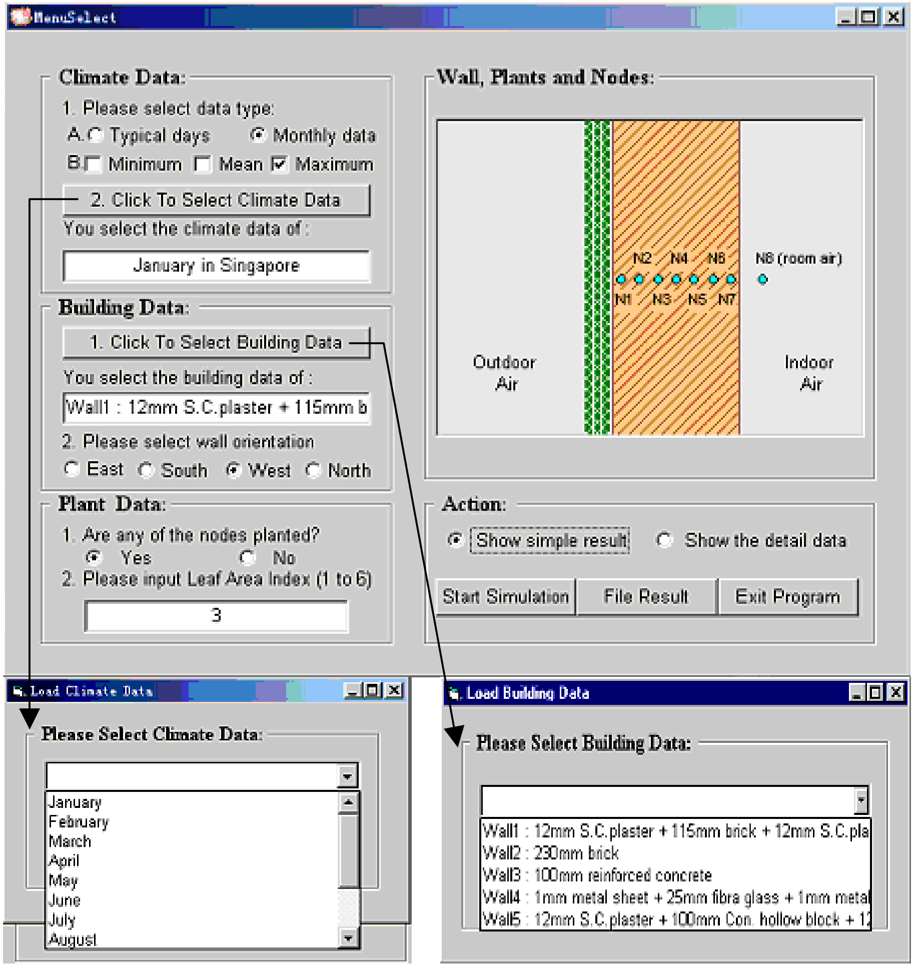
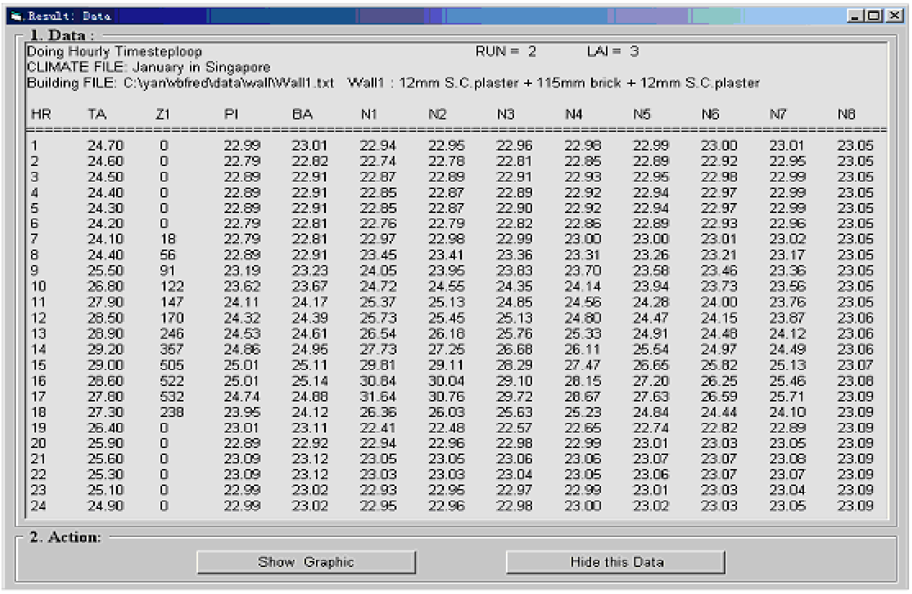


Figure 3. Process of using VEFRED-IVY.

4) Click Show Graphic button to see Figure of results (Figure 4)
5) Click File Result button to record results in a file named by user



Result: Data

1. Data :

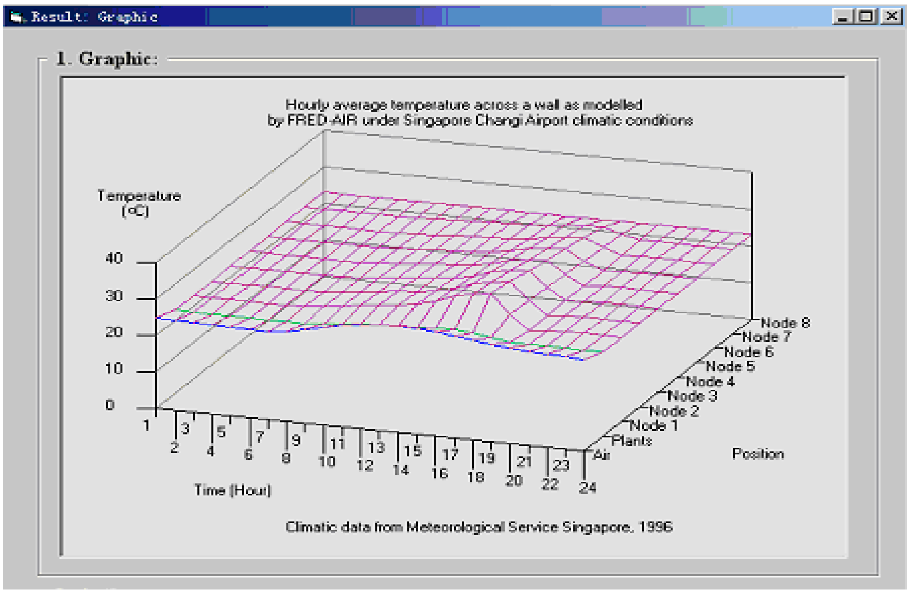
Doing Hourly Timesteploop RUN = 2 LAI = 3
CLIMATE FILE: January in Singapore
Building FILE: C:\yan\vbfred\data\wall\Wall1.txt Wall1 : 12mm S.C.plaster + 115mm brick + 12mm S.C.plaster

HR	TA	Z1	PI	BA	N1	N2	N3	N4	N5	N6	N7	N8
1	24.70	0	22.99	23.01	22.94	22.95	22.96	22.98	22.99	23.00	23.01	23.05
2	24.60	0	22.79	22.82	22.74	22.78	22.81	22.85	22.89	22.92	22.95	23.05
3	24.50	0	22.89	22.91	22.87	22.89	22.91	22.93	22.95	22.98	22.99	23.05
4	24.40	0	22.89	22.91	22.85	22.87	22.89	22.92	22.94	22.97	22.99	23.05
5	24.30	0	22.89	22.91	22.85	22.87	22.90	22.92	22.94	22.97	22.99	23.05
6	24.20	0	22.79	22.81	22.76	22.79	22.82	22.86	22.89	22.93	22.96	23.05
7	24.10	18	22.79	22.81	22.97	22.98	22.99	23.00	23.00	23.01	23.02	23.05
8	24.40	56	22.89	22.91	23.45	23.41	23.36	23.31	23.26	23.21	23.17	23.05
9	25.50	91	23.19	23.23	24.05	23.95	23.83	23.70	23.58	23.46	23.36	23.05
10	26.80	122	23.62	23.67	24.72	24.55	24.35	24.14	23.94	23.73	23.56	23.05
11	27.90	147	24.11	24.17	25.37	25.13	24.85	24.56	24.28	24.00	23.76	23.05
12	28.50	170	24.32	24.39	25.73	25.45	25.13	24.80	24.47	24.15	23.87	23.06
13	28.90	246	24.53	24.61	26.54	26.18	25.76	25.33	24.91	24.48	24.12	23.06
14	29.20	357	24.86	24.95	27.73	27.25	26.68	26.11	25.54	24.97	24.49	23.06
15	29.00	505	25.01	25.11	29.81	29.11	28.29	27.47	26.65	25.82	25.13	23.07
16	28.60	522	25.01	25.14	30.84	30.04	29.10	28.15	27.20	26.25	25.46	23.08
17	27.80	532	24.74	24.88	31.64	30.76	29.72	28.67	27.63	26.59	25.71	23.09
18	27.30	238	23.95	24.12	26.36	26.03	25.63	25.23	24.84	24.44	24.10	23.09
19	26.40	0	23.01	23.11	22.41	22.48	22.57	22.65	22.74	22.82	22.89	23.09
20	25.90	0	22.89	22.92	22.94	22.96	22.98	22.99	23.01	23.03	23.05	23.09
21	25.60	0	23.09	23.12	23.05	23.05	23.06	23.06	23.07	23.07	23.08	23.09
22	25.30	0	23.09	23.12	23.03	23.03	23.04	23.05	23.06	23.07	23.07	23.09
23	25.10	0	22.99	23.02	22.93	22.95	22.97	22.99	23.01	23.03	23.04	23.09
24	24.90	0	22.99	23.02	22.95	22.96	22.98	23.00	23.02	23.03	23.05	23.09

2. Action:

Show Graphic Hide this Data

a. Results shown by table



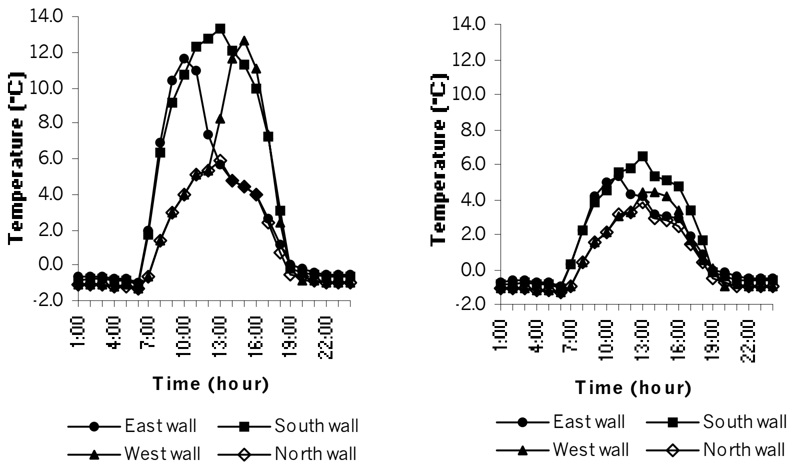
b. Results shown by figure

Figure 4. Results produced by VBFRED-IVY.

4. Parametric Testing

Singapore climatic data (dry bulb temperature, web bulb temperature, and global solar radiation, diffuse solar radiation and wind velocity on a wall surface) and thermal data of a local typical wall (12 mm Sand Cement Plaster + 115 mm Brick + 12 mm Sand Cement Plaster) are input in VBFRED-IVY to do the parametric testing. The walls with and without plants are modeled with the VBFRED-IVY to predict the thermal performance of plants on buildings in Singapore.

The research reveals that the thermal effects of plants are theoretically quite remarkable: the surface temperature on a planted wall can be up to 13°C lower than that on a non-planted wall - depending on surface reflectivity and orientation of the wall. The results show that it is more effective when plants are introduced on dark color wall than light color wall: the surface temperature reduced by plants on a dark color wall is much larger than plants on a light color wall (Figure 5).



a. Dark color wall (surface reflectivity= 0.3) *b.* Light color wall (surface reflectivity= 0.7)

Figure 5. Thermal effects of plants in reducing wall surface temperature predicted by VBFRED-IVY on walls in four orientations in clear day of December in Singapore.

4. Evaluation

Field measurements are carried on three planted walls in different orientations, and statistics method is applied to evaluate the simulation program. The results show that VBFRED-IVY is efficient.

4.1 FIELD MEASUREMENT

Field measurements were carried on for two weeks in national university of Singapore in November and December 2000. Three planted walls of Hon Sui Sen Memorial Library are selected: a east facing gray wall with Rhapis humilis (Lady palm), a south facing white wall with Bougainvillea glabra and a west facing gray wall with Rhapis humilis (Lady palm) (Figure 6). Instruments used in the field measurements include surface
thermometer, sling thermometer, and solar radiation with meter.

a. East facing gray wall *b.* West facing gray wall *c.* South facing white wall

Figure 6. Three planted walls selected in field measurement.

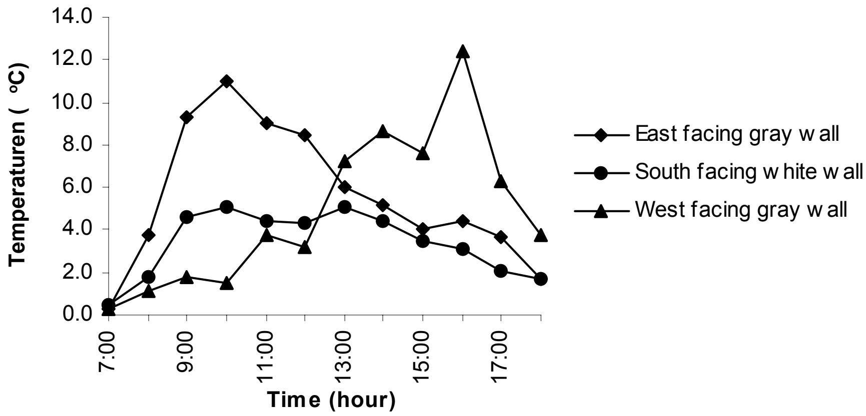


Figure 7. Measured thermal effects of plants in reducing wall surface temperature on walls in three orientations in partly cloudy day of December in Singapore.

The results of field measurements show that the thermal effects of plants are quite significant. For a west facing gray non-planted wall, the maximum surface temperature is around 42.6°C at 16:00 hr, while the surface temperature on a west facing dark color planted wall is only around 30.2°C. The measured results show that the surface temperature on a planted wall is up to 12.4°C lower than that on a non-planted wall. Following are the results of field measurement (Figure 7).

4.2 EVALUATION

The VBFRED-IVY is validated against field measurements. Measured climatic data (solar radiation on the wall, air temperature, web bulb temperature, and air movement velocity), and thermal data of a local typical wall (12 mm Sand Cement Plaster + 115 mm Brick + 12 mm Sand Cement Plaster) are input in VBFRED-IVY. Student's t-test is used to compare predicted results and measured results. In this comparison, there are 109 degrees of freedom. The comparison produces correlation coefficient of 0.96 significant at 99.9%.

Taking into account of the equipment error and the difficulty of thermal modeling, the present simulation model VBFRED-IVY may be considered satisfactory.

5. Conclusion

A computational tool, VBFRED-IVY has been developed on the base of FRED-AIR and FRED-IVY. This simulation program is used to model and analyze the thermal effects of plants on buildings under Singapore climatic conditions. Field measurements are carried on three planted walls in different orientations, and Student's t-test is applied to evaluate the simulation program. The results show that VBFRED-IVY is efficient considering the equipment error and difficulty of thermal modeling.

VBFRED-IVY has a friendly input and output interface, and flexible data inputting and result outputting methods. These advantages can let more researchers to make use of VBFRED-IVY without difficulty.

Due to the limitation of time, further work involving more improvements of the simulation program and advanced evaluation by more field measurements should be carried out to complement VBFRED-IVY.

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