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A RISK-BASED SENSOR PLACEMENT METHODOLOGY

May 15, 2006

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May 15, 2006

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LIST OF ABBREVIATED TERMS

AEGL	Acute Exposure Guideline Levels
AIHA	American Industrial Hygiene Association
ALOHA	Areal Locations of Hazardous Atmosphere
API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
DOE	United States Department of Energy
DTRA	Defense Threat Reduction Agency
EEGL	Emergency Exposure Guideline Level
ERPG	Emergency Response Planning Guidelines
GB	Gigabytes
GHz	Gigahertz
GML	Geography Markup Language
HPAC	Hazard Predication and Assessment Capability
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory Model
MHz	Mega-Hertz
NOAA	National Oceanic and Atmospheric Administration
NRC COT	National Research Council's Committee on Toxicology
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
RAM	Random Access Memory
SAMSON	Solar and Meteorological Surface Observation Network
SCIPUFF	Second-order Closure Integrated Puff Model
SPEGL	Short-Term Public Exposure Guidance Levels
WFS	Web Feature Service

ABSTRACT

A sensor placement methodology is proposed to solve the problem of optimal location of sensors or detectors to protect population against the exposure to and effects of known and/or postulated chemical, biological, and/or radiological threats. Historical meteorological data are used to characterize weather conditions as the frequency of wind speed and direction pairs.

The meteorological data drive atmospheric transport and dispersion modeling of the threats, the results of which are used to calculate population at risk against standard exposure levels. Sensor locations are determined via a dynamic programming algorithm where threats captured or detected by sensors placed in prior stages are removed from consideration in subsequent stages.

Moreover, the proposed methodology provides a quantification of the marginal utility of each additional sensor or detector. Thus, the criterion for halting the iterative process can be the number of detectors available, a threshold marginal utility value, or the cumulative detection of a minimum factor of the total risk value represented by all threats. The methodology quantifies the effect of threat reduction measures, such as reduced probability of one or more threats due to administrative and/or engineering controls.

1. INTRODUCTION

Placement of sensors and detectors at storage facilities and other locations with known threats is a critical aspect of any strategy to protect population potentially exposed to those threats. Yet, sensor placement techniques for detection of chemical and/or biological agents have yet to be standardized or universally adopted. For example, Sierra Monitor Corporation's "Gas Sensor Placement Guidelines" notes,

> There are no complete and definitive regulations or guidelines published by ISA, NFPA, UL, FM or other agencies that tell users where or how many gas sensors to use... Each gas leak possibility must be evaluated as a unique problem to assess the risk to people and property. The object of monitoring system design is to reduce the risk to people and property by responding to the gas leak.[1]

Current approaches to sensor and detector placement range from heuristics, to genetic algorithms,[2] to various optimization techniques.[3,4] Placement optimization objective functions vary for different types of sensors. For example, visual or geometric coverage is typically the objective function to be maximized for placement of surveillance cameras.[5–8] For point or area detections the objective is to maximize coverage of a geographic or geometric area.[9,10] Other approaches to plume detection focus on other criteria, such as time to detection or total sensor area coverage, and are concerned only with detecting any part of a plume.[2,4]

However, mere detection of a chemical or biological agent is insufficient to fully characterize the threat posed by the corresponding release. Rather, we suggest that the *effect on population* should be the primary factor in determining optimal sensor placement. Human effects provide a more useful objective function for any optimization related to chemical and biological detection, for effects on population represent the true consequences of failure to detect a release and subsequently evacuate and/or treat potentially impacted people.

Further, we wish to account for the variety of meteorological conditions (wind speed and direction) under which a threat might occur in a manner that is independent of the time of occurrence. Whereas other approaches assume a particular wind condition[2] and/or solve the sensor placement problem for a particular instant of time, a method is needed to place sensors in situations where the cost of their deployment does not allow rapid response to changing wind and other meteorological conditions.

A sensor placement algorithm and methodology for situations where a set of known or postulated threats is established, and the desire is to protect potentially affected population by detecting the threats whenever they might occur is proposed here. The key elements of the approach are:

- Risk, defined as population exposure and effects, is the basis of an optimization objective function;
- A *wind rose* specifying probabilities for wind speed and direction pairs is derived from historical meteorological data;
- Transport and dispersion and population exposure effects are calculated for known threats with respect to all wind speed and direction pairs; and
- Sensor locations are determined via a dynamic programming algorithm where the optimal location of the next sensor is computed in each iteration or stage.

The proposed methodology offers a defensible and reasonable foundation for a systematic, risk-based placement of sensors for known threats and a quantifiable mechanism for determining the marginal utility of each additional sensor. This leads to a qualified determination of the number and locations of sensors needed to adequately protect against a set of threats expressed as the percentage of the total risk from all threats combined that is captured or detected. Moreover, the proposed methodology is generally applicable and not dependent on locations, types of threats, sources of data, or specific models.

However, sensors are assumed to be *perfect detectors*, so that any amount of an agent or material passing through a sensor will be detected. The methodology does not account for a sensor's sensitivity to the concentration or mass of the material required for detection. There are two justifications for this assumption. First, the nature of the problem to be solved, toxic agents in sufficient quantities to pose a risk to population, implies material masses above any reasonable detection threshold for a sensor. The detectors used in the reference application of the methodology respond to quantities in the nanogram scale, respond within a few seconds, and are quickly saturated. Second, the problem to be solved is the location for sensors in general, irrespective of the particular sensing technology deployed.

In this paper the methodology and its algorithm are described, and results from applying the methodology at the Port of Memphis, Tennessee are presented.

2. METHODOLOGY

The proposed sensor placement methodology is built around a dynamic programming algorithm where each iteration (or algorithm stage) is an optimization solution for the next sensor location. Moreover, the objective function described in Sect. 2.2 distinguishes this optimization from other sensor placement optimizations. However, data gathering and computations preparing the inputs for the placement algorithm comprise much of the methodology. Descriptions of these inputs and the processes for generating them provide a background for understanding the optimization. Generally, the methodology has two parts: generating the inputs to the placement algorithm, and applying the algorithm.

2.1 INPUTS AND PARAMETERS

2.1.1 Threats

We begin with a set of known or postulated threats to detect. Each identified threat is modeled as an agent release for input to an atmospheric transport and dispersion model. The nature of the threat dictates the release definition. For example, a puncture in a storage tank might be modeled as a series of continuous releases at decreasing mass rates, and a complete container failure might be represented as an instantaneous release of all of an agent in liquid form. For the Port of Memphis threats are modeled as continuous releases of specific materials at specific release rates using the Hazard Prediction and Assessment Capability (HPAC).[11]

Regardless of the choice of dispersion model, the threat must be defined as accurately as the chosen model allows and should account for the agent mass as well as realistic release rates given the containment of the agent and the dynamics of phase changes that occur as the agent is expelled from a container.

Threat Factor. In many cases, each threat may be considered equally likely and/or of equal concern. If not, a weighting or factor may be assigned to each threat to represent its likelihood of occurrence. This factor is applied in the risk value calculation described in Sect. 2.2.1.

2.1.2 Exposure Levels

Dispersion models typically produce one or more of concentration, deposition, and dosage fields. However, these results do not relate directly to effects on population, and some correlation of the fields to effects is necessary.

For this methodology, dosage fields are required and are contoured by standard exposure limits and levels defined by the organizations such as the American Industrial Hygiene Association (AIHA), the National Research Council's Committee on Toxicology (NRC COT), and the Department of Energy (DOE). AIHA publishes the Emergency Response Planning Guidelines (ERPG). NRC COT publishes Acute Exposure Guideline Levels (AEGL), Emergency Exposure Guideline Levels (EEGLs) for the Department of Defense, and Short-Term Public Exposure Guidance Levels (SPEGL).[12] Temporary Emergency Exposure Limits (TEELs) are defined by DOE and used when AEGLs and ERPGs are unavailable.[12]

Dosages corresponding to standard exposure levels vary by material or agent. HPAC material descriptions include exposure level dosage values used for contouring the dosage field by exposure level.

Exposure Level Factor. These exposure levels are qualitative in nature and therefore must be quantified to contribute a term to the objective function. A quantitative factor is associated with each qualitative exposure level, where baseline levels such as TEEL-0 and ERPG-0 are given a factor of 1.0. Higher exposure levels, LCt90 (90% lethality) being the highest, are given higher factors applied to the risk value term. For example, in application of the methodology at the Port of Memphis LCt90 is assigned a value of 5.0, meaning one person exposed at LCt90 is equivalent to five persons exposed at TEEL-0.

An exposure level factor is used as a multiplier for the population count in contour polygons corresponding to the exposure level as described in Sect. 2.1.5. For our implementation, the assigned exposure level factors are stored in an input file in Java properties file format keyed by the exposure level name. Listed below is the file used for the sensor placement at the Port of Memphis.

```
LCt90=5.0
LCt50=3.0
ICt50=2.5
ICt5=2.0
TEEL-3-15m=1.75
TEEL-2-15m=1.5
TEEL-1-15m=1.25
TEEL-0-15m=1.0
ERPG-3-1h=1.75
ERPG-2-1h=1.5
ERPG-1-1h=1.0
```

2.1.3 Wind Rose

A useful representation of the range of meteorological conditions at a location is a *wind rose*. "A wind rose gives a very succinct but information-laden view of how wind speed and direction are typically distributed at a particular location".[13] Specifically, it specifies wind direction and speed pairs and their percentage of occurrence. The Natural Resources Conservation Service (NRCS) uses data from the Solar and Meteorological Surface Observation Network (SAMSON) to produce wind roses. Refer to Figure 1 for an example from the NRCS Web site. SAMSON consists of hourly observations from 1961 through 1990 at 237 National Weather Service (NWS) stations in the United States, Guam, and Puerto Rico. Thus, SAMSON is a good data source for computing wind roses at the stations covered, although any source of data can be used.

Direction and Speed Bins. Direction and speed bins in the rose must be chosen to be sufficiently small to capture variations in the observation values. The NRCS chooses 16 directions and six speeds, the 16 directions yielding a bin size of 22.5°. As applied at Memphis, the six speed bins are spaced by two m/s with centroid values 1, 3, 5, 7, 9, and 11. Speeds less than 1 m/s and greater than 11 m/s are assigned the respective boundary bins.

Station Locations. A single rose derived from thirty years of data provides a needed succinct representation of wind speed and direction in terms of percentage of occurrence. However, the NWS station(s) chosen to produce the rose must be close enough to (and representative of) locations of interest to be applicable. For application at the Port of Memphis, SAMSON data for Memphis International Airport is used. Note the airport is a couple of miles away, and there is no intervening terrain of consequence.

Boundaries for each (direction, speed) bin can be derived by examining the SAMSON data to determine the distribution of the bins. Appendix A. includes a description of the SAMSON format and some example data.

Regardless of the data source, a wind rose is required input. For our implementation the rose is read from a file containing the counts and percentages for each (direction, speed) bin, as shown below. Each data line following the header represents a single direction starting at 0° and moving clockwise. Columns are slash-separated counts and percentages for the direction as a whole and then for each of the six speed bins.

```
# Direction bin values:  0 22.5 45 67.5 90 112.5 135 157.5 180 202.5 225 247.5 270 292.5 315 337.5
# Speed bin values:  2 4 6 8 10
 0: 30447/13.71     14505/6.533    5722/2.577     5838/2.629     3556/1.602     683/0.308      143/0.064
 1: 13027/5.87      580/0.261      5425/2.443     4720/2.126     2000/0.901     271/0.122      31/0.014
 2: 11816/5.32      826/0.372      5560/2.504     4076/1.836     1239/0.558     106/0.048      9/0.004
 3: 10141/4.57      1084/0.488     5538/2.494     2810/1.266     653/0.294      51/0.023       5/0.002
 4: 15396/6.93      2548/1.148     9390/4.229     2825/1.272     559/0.252      56/0.025       18/0.008
 5: 7954/3.58       1073/0.483     4517/2.034     1860/0.838     446/0.201      39/0.018       19/0.009
 6: 12243/5.51      1269/0.572     6267/2.822     3322/1.496     1118/0.504     189/0.085      78/0.035
 7: 16578/7.47      1401/0.631     8091/3.644     4544/2.046     1966/0.885     429/0.193      147/0.066
 8: 30071/13.54     1503/0.677     12949/5.832    9951/4.482     4522/2.037     922/0.415      224/0.101
 9: 16737/7.54      540/0.243      5953/2.681     5983/2.695     3375/1.520     707/0.318      179/0.081
10: 14460/6.51      832/0.375      6130/2.761     4537/2.043     2456/1.106     431/0.194      74/0.033
11: 10178/4.58      689/0.310      4448/2.003     3240/1.459     1442/0.649     267/0.120      92/0.041
12: 9555/4.30       810/0.365      4152/1.870     2666/1.201     1415/0.637     359/0.162      153/0.069
13: 7520/3.39       464/0.209      2843/1.280     2220/1.000     1409/0.635     450/0.203      134/0.060
14: 8223/3.70       384/0.173      2388/1.075     2610/1.175     2104/0.948     581/0.262      156/0.070
15: 7695/3.47       341/0.154      2390/1.076     2609/1.175     1815/0.817     437/0.197      103/0.046
```

2.1.4 Population Data

A geographic population distribution is necessary to count the population affected by a release. Dispersion model dosage fields for each threat are contoured by standard exposure levels, and the population within the contours is counted. LandScan 2003 data at 30 arc-second resolution are used for sensor placement at the Port of Memphis.[14]

It should be noted that a population distribution that varies by time of day, most simply day versus night, would be particularly useful. *

2.1.5 Transport and Dispersion Calculation

As mentioned above, each identified threat is modeled as an agent or material release. The dispersion model should account for material characteristics such as evaporation rates and buoyancy as well as weather and environmental conditions during the dispersion process.

Many dispersion models are available, such as the Hybrid Single-Particle Lagrangian Integrated Trajectory Model (HYSPLIT)[15] the Areal Locations of Hazardous Atmosphere (ALOHA),[16] Vapor Liquid Solid Tracking (VLSTRACK), and many others.[17] Any system able to competently model the identified threats can be used. Our implementation of the proposed methodology uses the Second-order Closure Integrated Puff Model (SCIPUFF),[18,19] the transport and dispersion engine in the Hazard Prediction and Assessment Capability (HPAC).[11] In addition to the Defense Threat Reduction Agency's (DTRA) standardization of HPAC for hazard analysis, reasons for choosing HPAC include:

- Built-in modules for contouring calculated dosage fields;
- An extensive material library with dosage values corresponding to the standard exposure levels identified above;
- Built-in calculation of population using LandScan 2003 data;[14] and
- A validated transport and dispersion model accounting for meteorology, terrain, land cover, and other environmental conditions.

Computing Threat Effects. For each threat, the dispersion must be computed for each (direction, speed) bin in the wind rose. A rose with 16 directions and six speeds requires 96 computations for each threat. The dosage field resulting from a dispersion computation is then contoured by the exposure levels applicable to the agent/material released. With HPAC, contour calculations are provided in the dispersion engine library, and the population contained within each contour is counted against the 30 arc-second night time LandScan 2003 distribution.[20] For each exposure level, one or more contour polygons result. Once the computations are complete there is a set of exposure level contours for each threat and for each wind rose bin.

The duration for the model computation is specified in the threat definition and must be long enough to capture the full effects of a release on population. HPAC defaults the duration to four hours, but two hours is sufficient for the threats at the Port of Memphis.

---

[*] The LandScan USA project has produced day- and night-time high resolution population distributions at three arc-second resolution for some cities, including Memphis, but these data have yet to be vetted and released by the Department of Homeland Security.

Exposure Level Contours. Sensor placement at the Port is based on nine threats and a wind rose of 96 bins. Materials for the nine threats are such that six have three exposure levels and three have seven exposure levels. Thus, there are potentially 39 contours for each of the 96 meteorological conditions for a total of 3,744. Dosages for higher exposure levels are not always reached, but well over 3,100 individual contours resulted for the Memphis placement. [†]

Contours consist of one or more polygons defined as an outer ring and zero or more interior or hole rings. Contours themselves provide primary input to the placement optimization's objective function described in Sect. 2.2.

Figure 2 shows example contours from the dispersion computation for a threat displayed with Google Earth. Note the exposure level polygons and legend entries are coded by color.

2.1.6 Placement Grid

For determining sensor/detector locations the proposed methodology assumes point detectors will be deployed on a two-dimensional grid covering the spatial domain of potential locations. The height at which sensors are deployed is chosen to ensure their detection of any release of sufficient magnitude to threaten nearby population and account for other placement constraints, such as protection from tampering and accessibility for scheduled maintenance. Thus, the methodology selects placement in two dimensions.

Although no constraints on the grid geometry are imposed by the algorithm, *cells* in the grid are treated as if they uniformly define the potential detector placement space. A detector assigned to a cell can be placed anywhere within it. Further, one location within each cell is chosen as the *reference point*, representative of all the space covered by that cell. Thus, a rectilinear grid is a natural fit, but an adaptive grid is certainly possible. A uniform rectangular grid geometry is easiest to calculate and process.

For the Port of Memphis we use a uniform rectangular grid composed of roughly 27x30 m cells. This adequately represents the range of space in which discrete detector locations are possible. Each cell's center is chosen as its reference point. Environmental constraints such as power and network availability might eliminate some grid cells as possible sensor locations, as is the case in Memphis. Grid cell size calculations are given in Sect. B.1

2.1.7 Summary of Inputs and Parameters

It is useful to summarize the inputs and parameters and their impacts on accuracy and run time when applying the methodology.

Number and Kinds of Threat Scenarios. Clearly it is necessary to accurately represent the range of threat types and possible event locations which constitute the motivation for deploying sensors and/or detectors. The choice of threats to drive the placement process might be reduced if one or more threats are *similar* and have potential locations in close proximity to one another. *Similarity* involves many issues but would include material type, material mass and/or release rates, and the conditions of the release. For example, two threats with the same material and release rate but separated only by a hundred feet might be represented by a single threat.

[†] All dosage contour values are taken from HPAC material files which reference DOE document DKC-04-003.

When such reductions are made, the threat factor (see Sect. 2.1.1) should be set to weight the representative threat accordingly.

Decisions to reduce the number of threats are unavoidably subjective. It's a matter of whether or not computation time can be reduced by letting one threat represent one or more other threats while still adequately accounting for all potential risks.

Nine threat scenarios for the Port of Memphis against 96 (direction, speed) pairs yields 864 individual dispersion computations. This requires approximately 36 hours of compute time on a 3.0 gigahertz (GHz) Pentium 4 processor with 2 gigabytes (GB) of random access memory (RAM) and no other significant processor load. However, scenario calculation time varies significantly for different materials, terrain environments, and many other inputs to the dispersion model. Consider also that threat release dispersions are computed only once to produce contours used as inputs to the placement algorithm. Thus, the placement algorithm can be executed many times with varied parameters (e.g., grid sizes) without requiring recalculation of the threat dispersions.

Threat Factors. There is an inherent or implicit weighting of threats relative to each other from the types of materials and their respective toxic effects on any affected human population. Moreover, it is possible, if not probable, that the threats against which protection is desired are not equally likely or of equal concern. Applying an explicit factor to one or more threat scenarios is a means of representing these relative weights.

Threat factors are applied as multipliers to the population counts resulting for contours associated with threats. The multiplier is applied after the contour's exposure level factor and has no impact on computation time.

Exposure Level Factors. As described in Sect. 2.1.2 factors assigned to exposure levels are used as multipliers for population counts associated with those levels. Thus, they impact the results significantly and are a means of tuning the placement methodology to favor more toxic or less toxic releases. Assigning a value of 1.0 for all exposure levels treats all agents and materials equally, regardless of their toxicity. Conversely, toxicity can be emphasized with larger factors for higher exposure levels.

Wind Rose Granularity. Given that each threat scenario is computed for each wind rose bin, the number of bins has a significant impact on computation time and resources required for threat dispersion modeling. Thus, there is a trade-off between accuracy and number of threat computations.

Variability in the wind data must be considered. For example, if most direction observations are concentrated in one of a few direction clusters, it might be possible to specify a direction bin for each cluster. Outlier observations can be ignored if they occur infrequently enough to have insignificant impact on the results. Conversely, a wide spread of directions with little clustering might require more, smaller bins. Wind speeds require the same kind of analysis. Direction and speed bins need not be of equal size.

Population Data Resolution. Another accuracy-versus-computation time consideration is the resolution of the population data. In this case the relationship to computation time is more difficult to assess, for population data is accessed only during the contouring of a dosage field against an exposure level dosage value. Gridded population data such as LandScan 2003 are two-dimensional. Thus, doubling the resolution results in a four-fold increase in the number of population cells. However, population counts are essential in calculating risk values (refer to Sect. 2.2.1), and thus accuracy in the placement methodology result impels use of the highest resolution population distribution available.

Placement Grid Granularity. Similar to the population resolution, the granularity of the placement grid is a two-dimensional time-versus-accuracy consideration. A finer grid with smaller grid cells yields more distinct placement locations, so cell size must be chosen appropriately. Moreover, it is not necessary for grid cells to be uniform or symmetric. In situations where there is a fixed set of possible sensor locations, it may be more efficient to manually construct the grid to isolate these locations in their own cells. A uniform grid is likely more effective in situations where sensor placement is not constrained.

2.2 OPTIMIZATION OBJECTIVE FUNCTION

The key concept behind the sensor placement optimization is *risk*. Each threat's dispersion is computed for each (direction, speed) pair in the wind rose, and each dispersion computation results in a set of contours representing exposure levels appropriate for the agent/material released. For each contour we calculate a *risk value* in order to quantify the effects on population of the exposure represented by the contour. The cumulative risk across all contours for all threats and meteorological conditions is the total risk, and the objective is to detect or *capture* as much of the total risk as possible.

2.2.1 Risk Value

The risk value depends on many factors such as geometric contour, meteorological conditions, specific threat, exposure level, etc. It is convenient to parameterize the risk value with respect to the geometric contours in the form

$$\begin{aligned}\mathbf{R} &= \sum_{c \in C} R(c) \qquad (1)\\ &= \sum_{c \in C} F_c\, E_c\, P(c)\, N(c), \qquad (2)\end{aligned}$$

where

C	is the set of all contours for all threats and meteorological conditions
F_c	is the threat factor for contour c
E_c	is the exposure level factor for contour c
$P(c)$	is the probability of occurrence for the meteorological condition associated with c
$N(c)$	is the count of population within contour c

2.2.2 Captured Risk

We wish to detect as much of the total risk as possible by placing sensors or detectors in a placement grid. Thus, the objective function is expressed in terms of the placement grid as follows.

A contour is considered captured by a sensor in a placement grid cell if the reference point of the cell lies within the outer ring of one of the contour's polygons. We introduce a binary detection function $D(c, g_i)$ where c is a contour, and g_i is a particular grid cell:

$$D(c, g_i) = \begin{cases} 0 & if\ r_{g_i} \wedge p = \emptyset \qquad \forall p \in P_c \\ 1 & \text{otherwise} \end{cases} \tag{3}$$

where

P_c	is the set of polygons associated with contour c,
r_{g_i}	is the reference point for grid cell g_i, and
$x \wedge p$	tests for containment of point x in the outer ringer of polygon p.

Referring to Equation 2 we can calculate the risk accounted for (or captured) by placing a sensor in grid cell g_i as:

$$\begin{aligned} S(g_i) &= \sum_{c \in C} D(c, g_i)\, R(c) && (4) \\ &= \sum_{c \in C} D(c, g_i)\, F_c\, E_c\, P(c)\, N(c) && (5) \end{aligned}$$

Given a number of sensors n we want to place those sensors in a grid cell configuration $G = \{g_1, \cdots, g_n\}, g_i \neq g_1, \cdots, g_{i-1}$ resulting in the maximum captured risk:

$$\max_G S(G) \tag{6}$$

We make no attempt to solve the global optimization problem 6. Rather, we solve a sequence of weaker optimization problems by finding the optimal grid cell for placement one at a time. Thus, on the first iteration we find

$$\max_{g_1} S(g_1) \tag{7}$$

On the second iteration g_1 is already selected by the previous step, and we find

$$\max_{g_2} S(g_1; g_2), \quad g_2 \neq g_1 \tag{8}$$

Generally, for iteration i the cells $g_1, \cdots, g_{i-1}$ have been selected in the previous $i - 1$ iterations, and thus we find

$$\max_{g_i} S(g_1; \cdots; g_{i-1}; g_i) \tag{9}$$

2.2.3 Marginal Utility

A byproduct of calculating risk captured in a cell is a simple calculation of the marginal utility of placing a detector in that cell, the ratio of the captured risk to the total risk. We represent the marginal utility for grid cell g_i as U_{g_i}:

$$U_{g_i} = \frac{S(g_i)}{\mathbf{R}} \tag{10}$$

Upon successive iterations or stages in the placement algorithm described in Sect. 2.3, the sum of the $S(g_i)$ values for chosen grid cells yields the cumulative captured risk. The quotient of the cumulative captured risk and total risk yields the fraction of the total risk captured. Note this value is monotonically increasing.

2.3 PLACEMENT ALGORITHM

Once the inputs described in Sect. 2.1 have been gathered and computed, Equation 5 can be applied to compute the captured risk for each grid cell and then to determine the optimal cell in which to place a sensor. We execute a dynamic programming algorithm to choose sensor locations in sequence, terminating when one or more criteria are met.

2.3.1 Sensor Placement Stages

Each stage of the algorithm applies the equations to choose the optimal location for the next sensor, irrespective of locations chosen for subsequent stages. The *state* associated with each stage consists of the set of contours that have yet to be captured by a previous grid cell selection. On the first iteration no sensor locations have been chosen, and the state consists of all contours for all threats and meteorological conditions, represented by C in Equation 5.

A stage ends with the determination of which contours to include in the contour set for the next stage. Recalling the detection function of Equation 3, the contour set for stage $k+1$ is determined as follows:

$$C_{k+1} = \{c \in C_k : \quad D(c, g_k) = 0,\ g_k \text{ is the selected grid cell for stage } k\} \tag{11}$$

2.3.2 Termination Criteria

There are three criteria for terminating the placement algorithm. They can be applied independently or in combination.

Fixed number of sensors. There are a fixed number of sensors/detectors available to deploy, thus dictating the number of algorithm stages or iterations.

Cumulative detection threshold. The goal is to achieve a specified cumulative detection fraction or percentage, and sensors are placed until the threshold is reached. This criterion should be used in combination with the following one, and the specified threshold must be in the range $(0, 1)$.

Marginal utility threshold. Sensors are placed until the marginal utility for the most recent sensor falls below a specified value. The basis for the threshold could be a minimum benefit needed to justify the cost of an additional sensor. This threshold value also must be in the range $(0, 1)$.

2.3.3 Algorithm Steps

The placement algorithm is simple and operates on two sets of input data and a parameter. One input is the set of contours from the dispersion computation of all threats against all meteorological conditions and the resulting exposure level contouring, with the respective risk value for each contour. The second input is the set of cells comprising the placement grid with each cell's respective reference point. The parameter is the termination criterion/criteria. Pseudocode is given in Algorithm 1.

Algorithm 1 Place sensors

```
Require: $R$, the total risk
Require: $C$, the set of all contours and their risk values
Require: $G$, the set of all placement grid cells
$C' \leftarrow C$
$PlacementCellList \leftarrow$ empty
$CumCapturedRisk \leftarrow 0$
$Iteration \leftarrow 0$
$TerminateFlag \leftarrow$ false
while $TerminateFlag =$ false do
    compute $S(g_i) \quad \forall g_i \in G$ (Equation 5)
    $g' \leftarrow$ the optimal placement cell
    $PlacementCellList \leftarrow PlacementCellList + g'$
    $CumCapturedRisk \leftarrow CumCapturedRisk + S(g')$
    $G \leftarrow G - g'$
    $Iteration \leftarrow Iteration + 1$
    if termination criteria are met with $CumCapturedRisk, Iteration, S(g')/R$ then
        $TerminateFlag \leftarrow$ true
    else
        $C' \leftarrow$ the set of uncaptured contours (Equation 11)
    end if
end while
```

2.4 IMPLEMENTATION

The proposed methodology has been used to place Smiths Detection Centurion[21] detectors at the Port of Memphis. These detectors are capable of detecting all of the threats of concern at the Port. For that purpose the methodology has been implemented with Java components, Perl scripts, and Bourne shell scripts. These are described in step-wise order of their use.

2.4.1 Step 1, Compute a Wind Rose

The first step is to establish the wind rose used for dispersion calculations and to provide the probability of meteorological condition occurrence for computing contour risk values, the $P(c)$ term in Equation 5. The data file representation of a rose given in Sect. 2.1.3 is used in our implementation. Although the wind rose may be specified manually or derived through any means for use in the placement methodology, our implementation generates the rose from SAMSON data for Memphis International Airport.

Raw SAMSON data are fed to a Perl script (*Quantize.perl* referenced in scripts below) to produce the output shown in Sect. A.3. Subsequent processing is performed with Java components needing access to the wind rose data, and thus it is convenient to convert the results to Java properties file format via another Perl script (*PercentProps.build.perl*).

The latter script chooses centroid values as the mean between bin boundaries with the first and last bins handled specially. For the first bin, a lower bound value of 0 is assumed when calculating the centroid. For the last bin, a value of 1.0 (units are m/s) is added to the last boundary.

Sect. A.4 shows the the result of applying the conversion script against the wind rose data for Memphis International. Java properties files contain $key = value$ pairs, one per line. The key for this file is the concatenation of the centroid wind direction and speed values separated by an underscore.

Bourne shell commands to execute these scripts are given blow. The environment variable *SDIR* points to a filesystem directory containing compressed SAMSON files, one file per year, the format distributed by NOAA. The first two arguments to *Quantize.perl* are the SAMSON data file column indexes for the wind direction and speed, respectively. The next parameter specifies a particular month of each year to process, where *0* specifies all months. Remaining arguments are names of compressed data files to process.

```
$ Quantize.perl 18 19 0 $SDIR/*.z > all-months.rose
$ PercentProps.build.perl all-months.rose > all-months.bins.props
```

Output for this step, the *all-months.bins.props* file, is the content shown in Sect. A.4.

2.4.2 Step 2, Compute Threat Dispersions and Generate Contours

HPAC is the transport and dispersion model in our implementation. Server components from the HPAC 4.04 distribution are executed and accessed by client Java components we developed for batch processing. The client components accept an Extensible Markup Language (XML) document specifying a calculation and/or plot to perform and containing an HPAC project file with releases to model.

Sect. C.1 in Appendix C. lists one such request file used for analysis at the Port of Memphis with some sensitive data redacted. Wind direction and speed values are substituted in the *hpac:calculate/hpac:fixedWinds* element for *@direction@* and *@speed@* tokens, respectively, as shown below.

```
<hpac:fixedWinds>
  <hpac:direction>@direction@</hpac:direction>
  <hpac:speed>@speed@</hpac:speed>
</hpac:fixedWinds>
```

The *hpac:project* element's CDATA content is the HPAC project file. Specified in the *hpac:plot* element are the exposure level contours for the threat. For example, as per the chlorine material description in the HPAC material database, the 15 minute TEEL-0 exposure level for Cl_2 is 21.75 $mg \cdot min/m^3$, represented by the contour definition below:

```
<hpac:contour>
  <hpac:label>TEEL-0-15m</hpac:label>
  <hpac:value>21.75</hpac:value>
  <hpac:population>0.0</hpac:population>
</hpac:contour>
```

Output from the client components is a response XML document which includes plot contour results (if *hpac:plot* is specified in the request). Contours are represented as Web Feature Service (WFS) feature collections,[22] one collection per output time defined for the HPAC project in the request document. For the purposes of detector placement, it is the final model output time that is of interest, for this represents the maximum potential geographical extent of the release(s). (Intermediate output times represent snapshots of the dispersion before the full reach.) In turn, each feature collection consists of a feature member per exposure level contour defined in the plot portion of the request document. Each feature member corresponds to a contour c in Equation 5, is represented geometrically as a polygon, and includes the count of population contained within its polygon. Sect. C.3 includes a snippet from a result document.

An example Bourne shell command for executing the script for three threats named *threat-1*, *threat-2*, and *threat-3* follows:

```
$ for th in threat-1 threat-2 threat-3; do \
> Batch.run.sh $th \
> done
```

Batch.run.sh, listed in Sect. C.2, assumes a subdirectory exists for each threat, and the subdirectory contains a request file with a *.req.xml* extension for each wind direction and speed in the rose (refer to Sect. C.1). The result file with a *.out.xml* (refer to Sect. C.3) extension is produced for each request file.

Factors must be assigned to each of the exposure levels represented by contours as discussed in Sect. 2.2.1. Sect. 2.1.2 lists the factors applied for Memphis in the format used in subsequent processing steps. In examples given in subsequent sections, the file containing these exposure factors is named *effects.props*.

Finally, if threats are to be weighted relative to each other, those respective factors must be assigned as well. We specify these in another Java properties file. If this file is omitted, all threats are assigned a factor of 1.0, as is the case for the Port of Memphis. If an individual threat is not assigned in the file, it also assumes a factor of 1.0. Keys in the properties file are threat names. Example entries are given below specifying a factor of 2.0 for *threat1-mat1* and 1.5 for *threat1-mat2*. Examples reference this file by the name *threats.props*.

```
threat1-mat1=2.0
threat1-mat2=1.5
```

Outputs for this step are:

- Feature members corresponding to each contour resulting from the modeling of each threat against each wind (direction, speed) pair (in files named threat*.out.xml*),
- Assignment of exposure level factors (*effects.props*),
- Assignment of relative threat factors (*threats.props*).

2.4.3 Step 3, Specify Grid Geometry

Grid geometry is discussed in Sect. 2.1.6. For Memphis we assume a uniform rectangular grid which can be fully specified with a west longitude, south latitude, width and height in decimal degrees, and the number of grid columns and rows.

We represent the grid in an American Standard Code for Information Interchange (ASCII) file with a header line containing the said grid specification. Subsequent lines hold cell captured risk values accumulated during processing, one line per row and column values separated by spaces. A grid file with only a header line is treated as if the value for all grid cells is 0. Otherwise, when grid processing starts, the values for all cells are read from the file and are used to initialize the captured risk values accumulated in each cell. This allows placement processing to be performed incrementally. An example header line follows:

```
-90.14,35.08,0.05,0.03 182,134
```

This specifies a grid with a southwest corner at longitude 90.14 ° west and 35.08 ° north and a width and height of 0.05 ° and 0.03 °, respectively. The second pair of numbers indicates a grid size of 182 columns and 134 rows, an uneven arrangement resulting from the latitude covered by the grid and a desire for roughly 25x25 m grid cells. Calculations for the number of grid cells in this example is given in Sect. B.2.

Output for this step in preparing for the placement algorithm is a grid file containing only the header line specifying the uniform rectangular grid geometry. In following examples this file is named *combined.grid*.

2.4.4 Step 4, Run Iterative Placement Algorithm

After completion of the first three steps, all the inputs necessary to execute Algorithm 1 are available. Since dispersion computation results are stored as XML documents in files organized by threat and meteorological condition, our implementation processes contours accordingly. Substeps in the iterative algorithm follow.

Step 4.1, Build Contour Ignore List. Given our organization of computation results, it's more convenient to accomplish Line 16 in Algorithm 1 by computing the inverse $\overline{C}$, that is the set of captured contours.

On the first iteration, no sensor locations have yet been chosen, so this step is not performed. On the second and subsequent iterations, a list of contours which are not to be processed in the current iteration (the *ignore list*) is built. These are the contours captured or detected by any previously selected sensor locations, meaning the contours' outer polygon rings contain one of the selected grid cell reference points.

A Java component reads chosen detector or sensor location coordinates from one file and compares that against all feature member contours in the final (i.e., last model output time step) feature collection in dispersion computation result files. A Bourne shell command invoking the Java component and passing the necessary command-line arguments follows:

```
$ IgnoreList.run.sh \
> -pts 11-21.coord -o 11-21.ignore \
> threat-1/*.out.xml threat-2/*.out.xml
```

IgnoreList.run.sh is a script that invokes the Java component. In the example, the coordinates are read from the file *11-21.coord*, example contents for which are given below. Each line in the file specifies a coordinate for a selected grid cell reference point as a comma-delimited longitude and latitude in decimal degrees. All result files (*.out.xml* extension) in the *threat-1* and *threat-2* subdirectories are passed to the Java component for processing.

```
-90.11884722222221,35.08393888888889
-90.10180555555554,35.10097777777779
```

The generated output file, named *11-21.ignore* in the example command above, identifies the captured contours by the threat name, wind (direction, speed) bin, and exposure level separated by dots. Note the direction and speed value may also contain a dot for decimal values and are themselves delimited by an underscore. A few lines from an output file are listed below.

```
threat1-mat1-1.247.5_3.ERPG-3-1h
threat1-mat2-1.202.5_9.TEEL-0-15m
threat2-mat2-1.135_7.TEEL-1-15m
threat1-mat3-1.270_11.ERPG-2-1h
...
```

The first output line above specifies the *threat1-mat1-1* threat scenario, wind direction *247.5*, wind speed *3*, and exposure level *EPRG-3-1h*. The generated output file represents $\overline{C}$ in Algorithm 1 and serves as one of the inputs to the placement selection performed in the next step.

Step 4.2, Compute Placement Grid Values We now proceed to computing the captured risk values for all grid cells, the S values of Line 7 in Algorithm 1. Another set of Java components performs this computation. The example Bourne shell command below invokes the *Placement.run.sh* script which in turn invokes the Java component.

```
$ Placement.run.sh \
> -bins all-months.bins.props \
> -effects effects.props \
> -threats threats.props \
> -ignore 11-21.ignore \
> -grid minus-11-21.grid \
> threat-1/*.out.xml threat-2/*.out.xml
```

Command line arguments in this example are:

-bins Specifies the wind rose file described with an example in Sect. 2.1.3.
-effects Specifies the file with exposure level factors as described in Sect. 2.1.2.

-threats Specifies the file with threat factors as described in Sect. 2.1.1. An example is given in Sect. 2.4.2. If this option is not provided, all threats are assumed to have a factor of 1.0.

-ignore Specifies the file containing the contour ignore list described in Sect. 2.4.4.

-grid Specifies the grid file, the only option specifying a file that is both input and output. When the command is executed, the file contains only the header line defining the grid geometry, as described in Sect. 2.4.3.

The remaining arguments are the names of dispersion computation result files to process. Any contour in those results files which matches a threat, meteorological condition, and exposure level specified in the contour ignore file is not processed.

Step 4.3, Choose Sensor Location For situations where sensors may be located in any grid cell, the next optimal location is the cell with the highest accumulated risk value. Alternatively, there may be a finite and discrete set of possible sensor locations due to availability of power, line of sight for wireless networks, and similar constraints. For such cases yet another Perl script (*Grid.match.perl*) processes a list of possible locations against a grid file to produce a list of available grid cell locations in descending order of captured risk, $S(g_i)$.

Locations are specified in a file one per line as comma-separated longitude and latitude followed by a location identifier. Example input location lines follow.

```
-90.10701666666667,35.10132222222223 99
-90.10001666666668,35.10560555555556 98
-90.0979361111111,35.10634166666667 97
```

A few lines of output are listed below to illustrate the results. Each line represents a potential sensor location starting with the location identifier, followed by the cell column and row and finally the captured risk value for the cell.

```
11     84, 25 ->   72610.00
10     83, 27 ->   69470.00
13    101, 38 ->   68320.00
14    102, 28 ->   68240.00
12     93, 35 ->   68130.00
```

Step 4.4, Compute the Marginal Utility Once a cell is selected for sensor placement in the current stage or iteration its risk value $S(g_i)$ is added to the cumulative captured risk as per Line 10 of Algorithm 1.

Termination criteria are examined against the number of sensors placed, the marginal utility of the most recent placement, and/or the cumulative captured risk.

3. RESULTS

The approach described here has been applied to the placement of chemical detectors at the Port of Memphis to mitigate risks associated with a set of threat scenarios defined in prior analysis of the Port's vulnerabilities. The threats were distilled to nine representative scenarios in three different locations and involving a specific set of materials. Sensor locations were constrained to roughly 30 locations around the Port area due to availability of power and other considerations. Results of applying the methodology are presented in tabular and graphic form.

Wind rose data for the Port area are shown in Sect. A.3. Exposure level factors used are exactly those shown in Sect. 2.1.2, and all nine threats are considered equally likely.

Table 1 is a summary of the results of applying the methodology at the Port of Memphis. Each successive stage represents a computation of the optimal cell location against all contours not captured by a previously selected cell. The total risk is 252,060.

Table 1: Summary of placement results at the Port of Memphis.

Stage	Highest Cell Value	Detector Site	Detector Cell Value	Marginal Utility	Cumulative Captured Risk
1	132300	11	124600	49.43%	49.43%
2	86420	21	74300	29.48%	78.91%
3	36090	01	32800	13.01%	91.92%
4	12340	25	3492	1.39%	93.31%
5	8854	20	2400	0.95%	94.26%

A visual representation of the placement process is given in a succession of images showing the grid overlaid on the Port area. Grid cells are colored with a 224-element spectrum colormap starting with blue for low cumulative captured risk values and moving to cyan, green, yellow, orange, and then red for the highest values. Appendix D. lists the full results for available sensor locations in the five stages.

Figure 3 depicts the grid for the first stage, when all contours are included in the placement computation. Possible sensor locations are indicated with circles. Note Table 1 shows the stage-one maximum cell capture risk value is 132,300, but that cell does not contain one of the possible sensor locations. Of the possible locations, the cell containing Site *11* has the highest value, 124,600, and thus it is the optimal available location for the first sensor.

Figure 4 depicts the grid for the second stage. All contours captured by the cell containing Site *11* are ignored in this iteration. The figure illustrates the remaining areas of the grid containing high values. Again, the cell with the highest value does not contain a possible location site, but Site *21*'s cell (unlabeled, adjacent to Site *22* in the image) has the highest value among the possible locations.

Figure 5 depicts the grid for the third iteration. All contours captured by the cells containing Sites *11* and *21* are ignored. All that remains is the relatively lower valued area in the western end of the Port area. The cell with the highest value among those containing possible detector locations contains Site *01*.

Figure 6 depicts the grid for the fourth stage. At the resolution of the colormap used for the grid depiction, no significant risk value remains to be captured or detected. However, Table 1 shows Site *25* as leading possible locations in capturing what risk value remains. Note the marginal utility has fallen below two percent in this iteration, confirming what one can deduce from the visual representation in the image.

After completion of five placement stages 94.26% of the total risk for all nine threats has been captured by the five sites. Base on criteria established for the Port, stage five is the last.

4. FUTURE WORK

Weather is arguably the most important factor in sensor placement. In the current methodology, the wind rose is derived with uniformly sized direction and speed bins. This can be improved with a quantization based on a classical method such as Lloyd I or II[23] in order to reduce the number of rose bins and/or improve the accuracy of the rose's representation of meteorological conditions. Further, weather conditions tend to be seasonal. Seasonal differences can be derived from historical meteorological data to produce seasonal wind roses which can be used to generate seasonal sensor locations.

Another factor that could be included in determining sensor location is time to detection. The binary detection function of Equation 3 could be modified to include a factor for the time to detect the release at the grid cell reference point. Instead of adding all the contour's risk value to the cell's captured risk, $S(g_i)$, the risk value added would be proportional to the time of detection. Whether or not this relationship should be linear must be investigated, but it is clear a grid cell with a shorter time to detection is preferred over one with a longer time to detection, and the current accumulation of the captured risk for each cell does not include this factor.

For engineering cost/benefit analyses, the methodology and projected costs for deploying sensor networks can be used to objectively compare the benefits of deploying sensors versus using various levels of administrative and engineering controls to reduce risk. Thus, the methodology could be used in an iterative manner to derive an optimum combination of administrative and engineering controls and sensor deployments to reduce threats.

5. SUMMARY

The sensor placement methodology proposed here attempts to solve the problem of locating sensors or detectors to protect against a set of known and/or postulated threats. An objective function based on population exposure and effects is used to solve a series of local optimizations. Historical meteorological data are used to characterize wind speed and direction and thus drive atmospheric transport and dispersion modeling of the threats, the results of which are used to calculate population at risk in various exposure levels. Sensor locations are determined with a dynamic programming algorithm whereby threats captured or detected by sensors placed in prior stages are not accounted for in subsequent stages.

Moreover, the proposed methodology provides a quantification of the marginal utility of each additional sensor or detector. Thus, the criterion for halting the iterative process can be the number of detectors available, a threshold marginal utility value, and/or the cumulative capture of a minimum factor of the total risk value represented by all threats.

References

1. Sierra Monitor Corporation. *Gas Sensor Placement Guidelines*, 1991. Application Data Sheet ADS-001.
2. K. Obenschain, J. Boris, and G. Patnaik. Using ct-analyst to optimize sensor placement. *Proc. SPIE: Chemical and Biological Sensing V*, 5416:14–20, August 2004.

3. Y. Chen, K. Moore, and Z. Song. Diffusion boundary determination and zone control via mobile actuator-sensor networks (mas-net): challenges and opportunities. In *Proc. SPIE: Intelligent Computing: Theory and Applications*, volume 5421, pages 102–113, 2004.

4. H. Ishida et al. Plume-tracking robots: A new application of chemical sensors. *Biological Bulletin*, 200:222–226, 2001.

5. H. Gonzalez-Banos and J. Latombe. A randomized art-gallery algorithm for sensor placement. In *Proc. Seventeenth Annual Symposium on Computational Geometry, SCG 2001*. ACM, June 2001.

6. I. Volkan Isler. *Algorithms for sensor placement and assignment*. University of Pennsylvania. presentation.

7. F. Prieto et al. Cad-based range sensor placement for optimum 3d data acquisition. *Machine Vision and Applications*, 15(2):76–91, December 2003.

8. Y. Zou and K. Chakrabarty. Sensor deployment and target localization for tactical surveillance. *ACM Transactions on Embedded Computing Systems*, 3:61–91, February 2004.

9. S.S. Dhillon and K. Chakrabarty. Sensor placement for effective coverage and surveillance in distributed sensor networks. *Journal of Parallel and Distributed Computing*, 64(7):788–798, July 2004.

10. S.S. Dhillon, K. Chakrabarty, and S.S. Iyengar. Sensor placement for grid coverage under imprecise detections. In *Proc. Fifth International Conference on Information Fusion*, volume 2, pages 1581–1587, July 2002.

11. Defense Threat Reduction Agency. *Hazard Prediction and Assessment Capability (HPAC)*. http://www.dtra.mil/Toolbox/Directorates/td/programs/acec/hpac.cfm.

12. National Oceanic and Atmospheric Administration. *Public Exposure Guidelines*. http://response.restoration.noaa.gov/cameo/locs/expguide.html.

13. Natural Resources Conservation Service, U.S. Department of Agriculture. *Wind Rose Data*. http://www.wcc.nrcs.usda.gov/climate/windrose.html.

14. Oak Ridge National Laboratory. *LandScan Main Page*, 2002. http://www.ornl.gov/sci/gist/landscan/.

15. Air Resources Laboratory, National Oceanic and Atmospheric Administration. *Hybrid Single-Particle Lagrangian Integrated Trajectory Model*. http://www.arl.noaa.gov/ready/hysp_info.html.

16. National Oceanic and Atmospheric Administration. *ALOHA*. http://response.restoration.noaa.gov/cameo/aloha.htm.

17. Modeling and Simulation Information Analysis Center, Defense Modeling and Simulation Office. *Models, simulations, and other resources*, 2002. http://www.msiac.dmso.mil/wmd/msres.asp.

18. R.I. Sykes, C.P. Cerasoli, and D.S. Henn. The representation of dynamic flow effects in a lagrangian puff dispersion model. *J. Haz. Mat.*, 64:223–247, 1999.

19. R.I. Sykes and R.S. Gabruk. A second-order closure model for the effect of averaging time on turbulent plume dispersion. *J. Appl. Met.*, 36:165–184, 1997.

20. S.F. Parker. *The HPAC Tool Application Programming Interface, HPAC Version 4.0.* Titan Corporation, 2000.

21. Smiths Detection. *Centurion-LS*, 2002. http://trace.smithsdetection.com/products/Default.asp?Product=42-&section=Life%20Sciences.

22. Open Geospatial Consortium, Inc. *Web Feature Service Implementation Specification, Version 1.0.0*, September 2000.

23. S.P. Lloyd. Least squares quantization in pcm. *IEEE Transactions on Information Theory*, pages 129–136, March 1982.

24. R. Bellman. *Dynamic Programming.* Princeton U. Press, 1957.

25. O.S. Benli. Dynamic programming. 1999. http://benli.bcc.bilkent.edu.tr/ omer/research/dynprog.html.

26. S.M. Brennan, A.M. Mielke, and D.C. Torney. Radiation detection with distributed sensor networks. *IEEE Computer*, pages 57–59, August 2004.

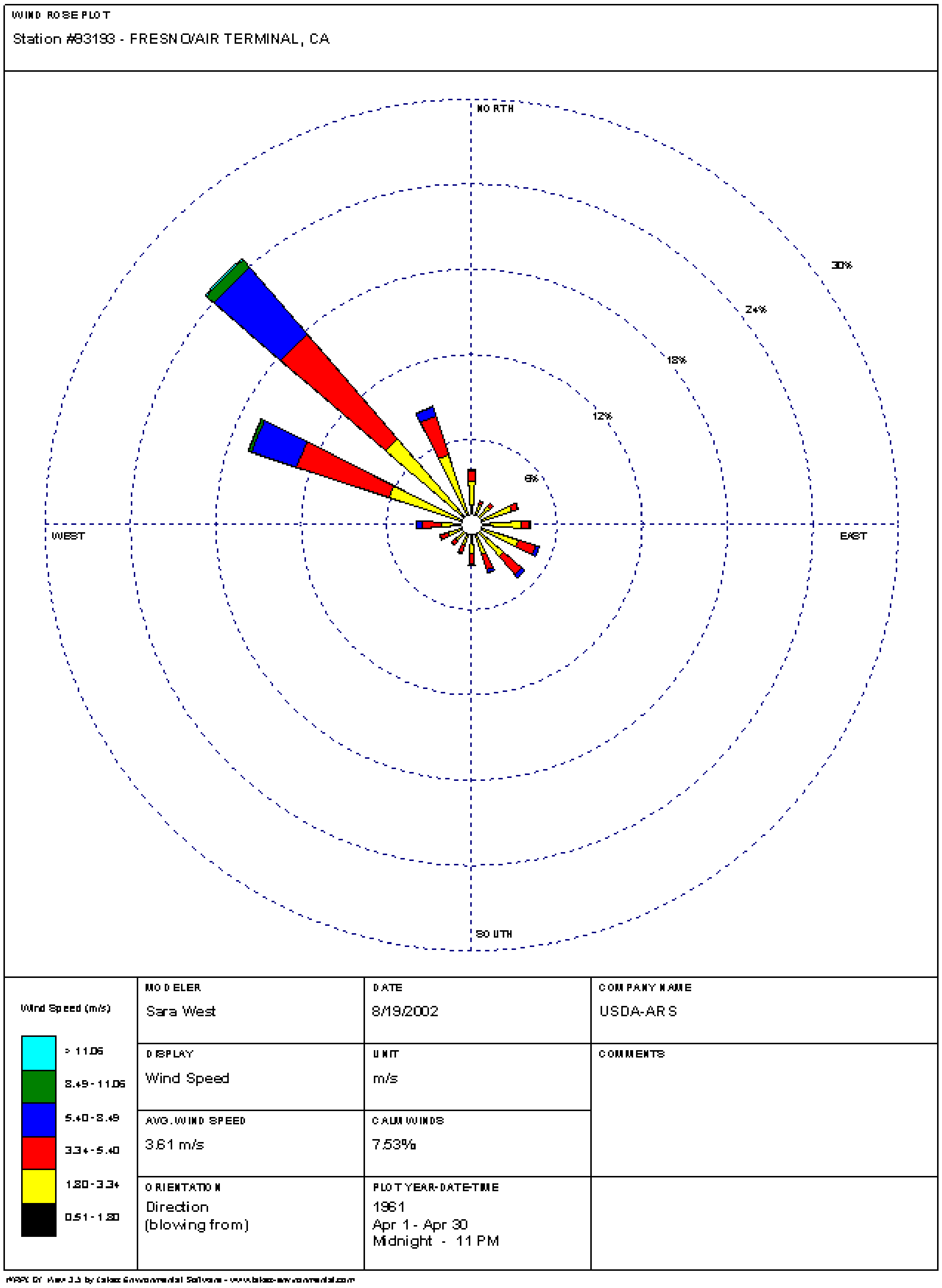
27. R.W. Lee. Moving the hazard prediction and assessment capability to a distributed, portable architecture. Technical Report ORNL/TM-2002/145, Oak Ridge National Laboratory, August 2002.

28. K.B. Lim. A disturbance rejection approach to actuator and sensor placement. *AIAA Journal of Guidance, Control, and Dynamics*, 20(1):202–204, 1997.

29. The Perl Foundation. *The Perl Directory*, 2006. http://www.perl.org.

30. Python Software Foundation. *Python Programming Language*, 2006. http://www.python.org.

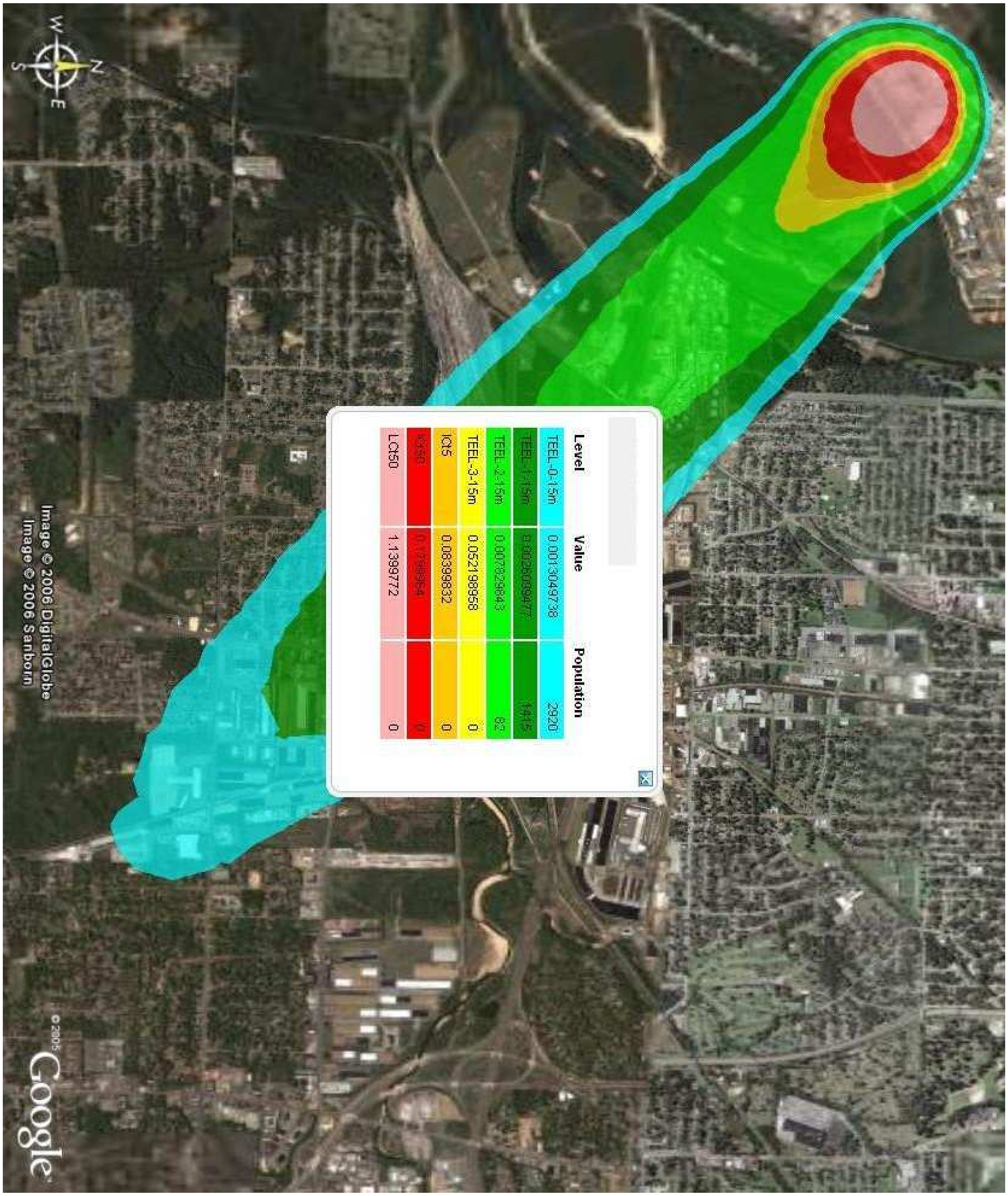
31. D. Ucinski. Optimal sensor placement in parameter estimation of distributed systems. In *Fourteenth International Symposium on Mathematical Theory of Network and Systems*, June 2000.



Station #93193 - FRESNO/AIR TERMINAL, CA

MODELER Sara West	DATE 8/19/2002	COMPANY NAME USDA-ARS
DISPLAY Wind Speed	UNIT m/s	COMMENTS
AVG. WIND SPEED 3.61 m/s	CALM WINDS 7.53%	
ORIENTATION Direction (blowing from)	PLOT YEAR-DATE-TIME 1961 Apr 1 - Apr 30 Midnight - 11 PM	

Fig. 1: Sample wind rose.



Level	Value	Population
TEEL-0-15m	0.0013049738	2920
TEEL-1-15m	0.0026099477	1415
TEEL-2-15m	0.007829843	82
TEEL-3-15m	0.052198958	0
ICt5	0.08399832	0
ICt50	0.1799864	0
LCt50	1.1399772	0

Fig. 2: Sample contours from a threat dispersion computation.

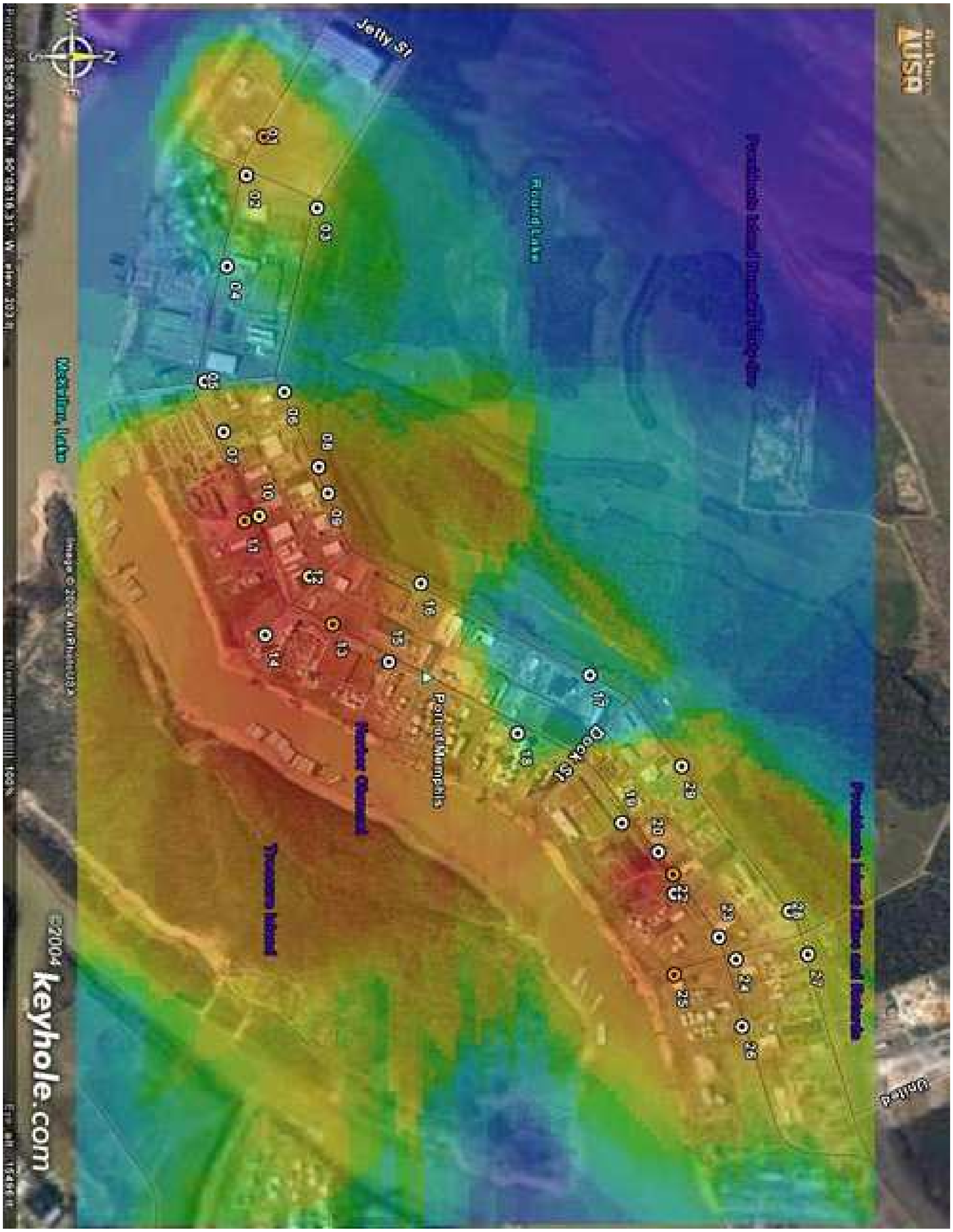


Fig. 3: Placement grid after the first stage.

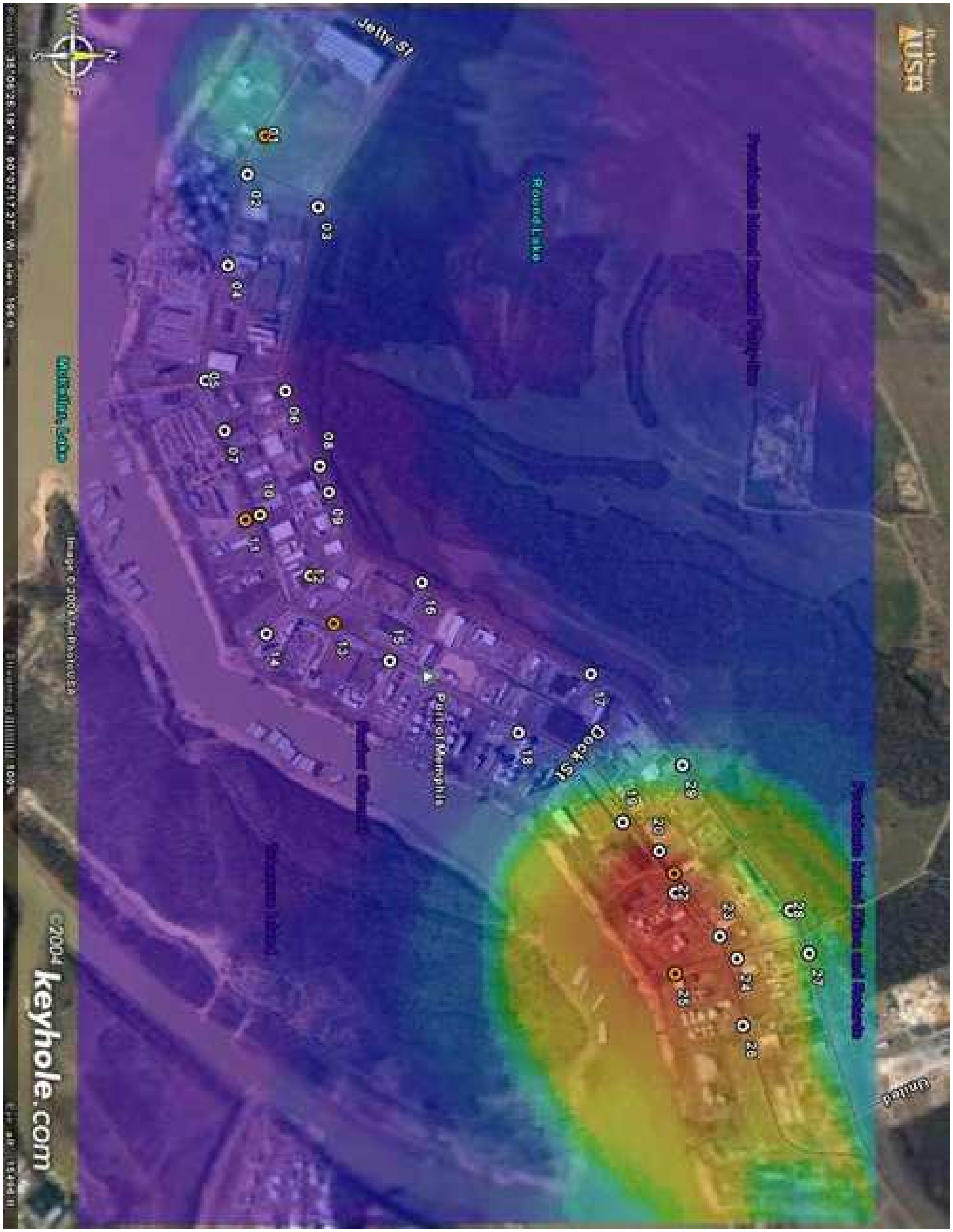


Fig. 4: Placement grid after the second stage.

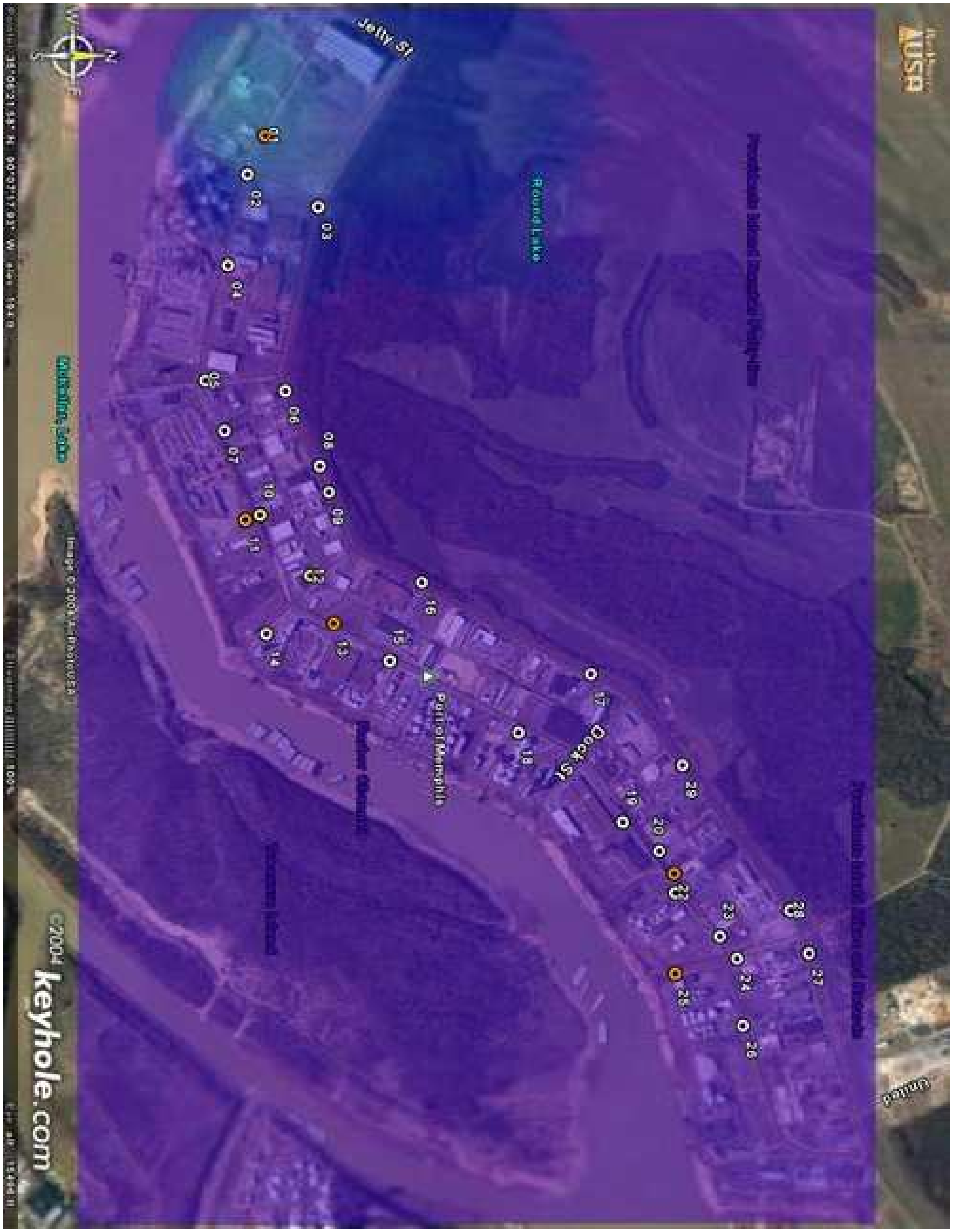


Fig. 5: Placement grid after the third stage.

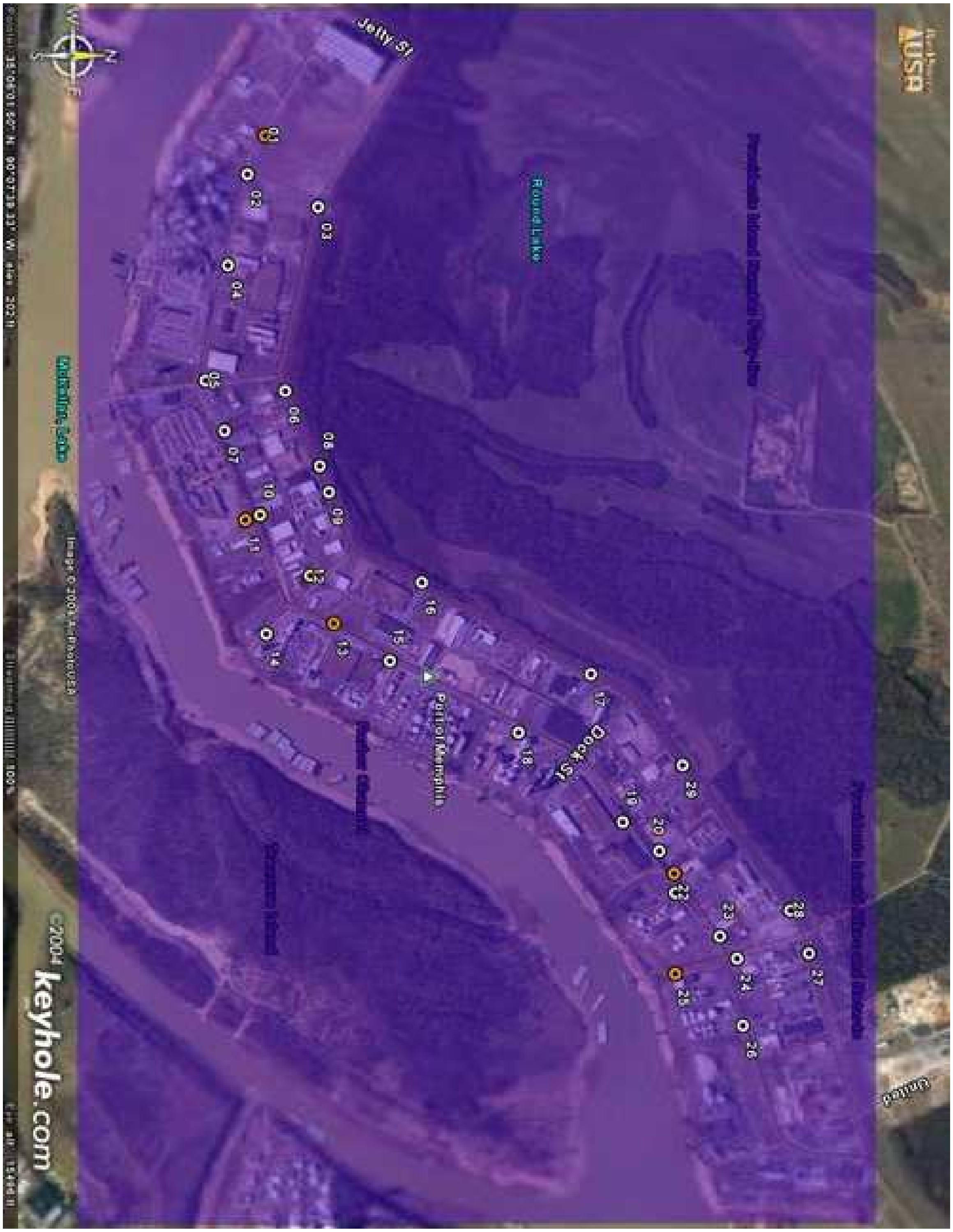


Fig. 6: Placement grid after the fourth stage.

A. SAMSON DATA PROCESSING

A.1 SAMSON DATA FIELD DESCRIPTIONS

Position	Description
	Year, month, day, hour, observation indicator
1	Extraterrestrial horizontal radiation
2	Extraterrestrial direct normal radiation
3	Global horizontal radiation
4	Direct normal radiation
5	Diffuse horizontal radiation
6	Total cloud cover
7	Opaque cloud cover
8	Dry bulb temperature
9	Dew point temperature
10	Relative humidity
11	Station pressure
12	Wind direction
13	Wind speed
14	Visibility
15	Ceiling height
16	Present weather
17	Precipitable water
18	Broadband aerosol optical depth
19	Snow depth
20	Days since last snowfall
21	Hourly precipitation amount and flag

A.2 SAMSON RAW DATA SNIPPET

The data below are for the first and last days of January, 1990. In the first three records (hours one through three), the respective wind directions are 230, 0, and 250 °, and the respective speeds are 2.1, 0.0, and 2.1 m/s.

```
13893 MEMPHIS                TN  -6  N35 03  W089 59    87
90  1  1  1    0    0    0 ?0    0 ?0    0 ?0  5  3   2.2   -.6  82 1011 230  2.1  16.1 77777 0999999999   1099999.   0  1      0
90  1  1  2    0    0    0 ?0    0 ?0    0 ?0  2  2    .6  -1.7  85 1011   0   .0  24.1 77777 0999999999   1099999.   0  1
90  1  1  3    0    0    0 ?0    0 ?0    0 ?0  0  0   1.7  -2.2  76 1012 250  2.1  24.1 77777 0999999999   1099999.   0  1
90  1  1  4    0    0    0 ?0    0 ?0    0 ?0  0  0   1.1  -2.2  79 1012 210  2.1  24.1 77777 0999999999   1099999.   0  1
90  1  1  5    0    0    0 ?0    0 ?0    0 ?0  0  0    .6  -1.7  85 1013 250  2.1  24.1 77777 0999999999   1099999.   0  1
90  1  1  6    0    0    0 ?0    0 ?0    0 ?0  0  0  -1.1  -3.3  85 1014 270  1.5  24.1 77777 0999999999    999999.   0  1
90  1  1  7    0    0    0 ?0    0 ?0    0 ?0  1  1    .0  -2.2  85 1015 230  1.5  24.1 77777 0999999999   1099999.   0  1
90  1  1  8  108 1132   45 G5  310 G4   15 G5  1  1  -1.1  -2.8  89 1016   0   .0  24.1 77777 0999999999    9  .026   0  1
90  1  1  9  322 1415  170 G5  478 G4   61 G5  2  2   2.8  -1.1  76 1017 330  2.1  32.2 77777 0999999999   10  .026   0  1
90  1  1 10  520 1415  335 G4  802 G4   40 G5  1  1   5.0  -1.7  62 1018 330  3.6  32.2 77777 0999999999   10  .026   0  1
90  1  1 11  662 1415  480 G4  925 G4   47 G5  0  0   6.7  -1.7  56 1018  30  3.6  32.2 77777 0999999999   10  .026   0  1
90  1  1 12  737 1415  530 G4  920 G4   50 G5  0  0   7.2  -1.1  56 1018  30  2.1  32.2 77777 0999999999   10  .026   0  1
90  1  1 13  741 1415  508 G4  737 G4  122 G5  2  2   7.8  -2.8  48 1017  50  1.5  32.2 77777 0999999999    9  .026   0  1
90  1  1 14  672 1415  457 G4  854 G4   52 G5  1  1   7.2  -3.3  47 1017 300  1.5  32.2 77777 0999999999    9  .026   0  1
90  1  1 15  536 1415  354 G5  716 G5   83 G5  4  3   7.8  -3.9  44 1018 310  2.6  32.2 77777 0999999999    9  .026   0  1
90  1  1 16  342 1415  138 G5  133 G5  106 G5 10  7   7.2  -3.3  47 1018 350  1.5  32.2  7620 0999999999    9  .026   0  1
90  1  1 17  123 1250   44 G5   57 G5   38 G5  8  4   4.4  -2.8  60 1018 340  3.6  32.2 77777 0999999999    9  .026   0  1
90  1  1 18    0    0    0 ?0    0 ?0    0 ?0  8  4   2.8  -2.2  70 1019 290  2.6  32.2 77777 0999999999   1099999.   0  1
```

```
 90  1  1 19    0    0    0 ?0    0 ?0    0 ?0  6  2   2.2  -2.2  73 1019 300  2.1  32.2 77777 0999999999  1099999.   0  1
 90  1  1 20    0    0    0 ?0    0 ?0    0 ?0  3  1   2.8  -1.7  73 1020 260  2.1  24.1 77777 0999999999  1099999.   0  1
 90  1  1 21    0    0    0 ?0    0 ?0    0 ?0  0  0   1.7  -1.1  82 1020   0   .0  24.1 77777 0999999999  1099999.   0  1
 90  1  1 22    0    0    0 ?0    0 ?0    0 ?0  0  0    .0  -2.8  82 1020   0   .0  19.3 77777 0999999999   999999.   0  1
 90  1  1 23    0    0    0 ?0    0 ?0    0 ?0  0  0   -.6  -2.8  85 1020   0   .0  16.1 77777 0999999999   999999.   0  1
 90  1  1 24    0    0    0 ?0    0 ?0    0 ?0  0  0  -2.2  -3.9  89 1020 160  2.6  14.5 77777 0999999999   999999.   0  1
 90  1  2  1    0    0    0 ?0    0 ?0    0 ?0  0  0  -2.2  -3.9  89 1019 130  2.1  24.1 77777 0999999999   999999.   0  2
 90  1  2  2    0    0    0 ?0    0 ?0    0 ?0  0  0  -2.2  -3.9  89 1020   0   .0  24.1 77777 0999999999   999999.   0  2
 90  1  2  3    0    0    0 ?0    0 ?0    0 ?0  7  3  -2.2  -3.9  89 1020   0   .0  16.1 77777 0999999999   999999.   0  2
 90  1  2  4    0    0    0 ?0    0 ?0    0 ?0  8  3  -2.8  -4.4  89 1019   0   .0  12.9 77777 0999999999   899999.   0  2
 90  1  2  5    0    0    0 ?0    0 ?0    0 ?0  6  2  -1.1  -3.3  85 1019 160  1.5  12.9 77777 0999999999   999999.   0  2
 90  1  2  6    0    0    0 ?0    0 ?0    0 ?0  8  5    .0  -2.2  85 1019 160  2.1  16.1  7620 0999999999  1099999.   0  2
.
.
.
 90 12 30 23    0    0    0 ?0    0 ?0    0 ?0 10 10  -4.4  -8.3  75 1021 350  5.2  19.3   520 0999999999   799999.   0  7
 90 12 30 24    0    0    0 ?0    0 ?0    0 ?0 10 10  -4.4  -8.3  75 1022 350  5.7  16.1   460 0999999999   799999.   0  7
 90 12 31  1    0    0    0 ?0    0 ?0    0 ?0 10 10  -5.0  -9.4  71 1022  20  6.7  19.3   520 0999999999   699999.   0  0
 90 12 31  2    0    0    0 ?0    0 ?0    0 ?0 10 10  -5.6 -10.0  71 1023 360  5.7  19.3   520 0999099999   699999.   0  0
 90 12 31  3    0    0    0 ?0    0 ?0    0 ?0 10 10  -5.6  -9.4  74 1023  20  5.7  24.1   460 0999099999   699999.   0  0
 90 12 31  4    0    0    0 ?0    0 ?0    0 ?0 10 10  -6.1 -10.6  71 1023  30  5.7  24.1   460 0999999999   699999.   0  0
 90 12 31  5    0    0    0 ?0    0 ?0    0 ?0 10 10  -6.7 -10.6  74 1023  10  4.6  24.1   460 0999999999   699999.   0  0
 90 12 31  6    0    0    0 ?0    0 ?0    0 ?0 10 10  -6.7 -10.6  74 1024  20  5.2  24.1   400 0999999999   699999.   0  0
 90 12 31  7    0    0    0 ?0    0 ?0    0 ?0 10 10  -6.1 -10.0  74 1024  30  4.6  19.3   370 0999999999   699999.   0  0
 90 12 31  8  108 1132   26 G5    0 G4   26 G5 10 10  -6.7 -10.6  74 1024  30  4.6  16.1   400 0999999999   6  .089   0  0
 90 12 31  9  322 1415   87 G5    0 G4   87 G5 10 10  -6.7 -10.6  74 1025  50  5.2  16.1   400 0999999999   6  .089   0  0
 90 12 31 10  520 1415  157 G4    1 G4  156 G5 10 10  -6.1 -10.0  74 1026  60  5.2  16.1   370 0999999999   6  .089   0  0
 90 12 31 11  661 1415  430 G5  679 G5  113 G5  4  4  -4.4  -9.4  69 1025  40  5.2  16.1 77777 0999999999   6  .089   0  0
 90 12 31 12  736 1415  466 G4  618 G4  144 G5  2  2  -2.8  -7.8  69 1025  30  5.7  19.3 77777 0999999999   7  .089   0  0
 90 12 31 13  739 1415  493 G4  763 G4   95 G5  1  1  -2.2  -7.8  66 1023  50  4.1  19.3 77777 0999999999   7  .089   0  0
 90 12 31 14  670 1415  444 G4  757 G4   85 G5  1  1  -1.7  -7.2  66 1023  20  4.1  24.1 77777 0999999999   7  .089   0  0
 90 12 31 15  533 1415  328 G4  691 G4   67 G5  1  1   -.6  -7.2  61 1022  50  5.2  24.1 77777 0999999999   7  .089   0  0
 90 12 31 16  340 1415  181 G5  471 G4   68 G5  2  2  -1.1  -7.2  64 1022  60  5.2  24.1 77777 0999999999   7  .089   0  0
 90 12 31 17  120 1250   38 G5  118 G4   26 G5  2  2  -1.7  -7.2  66 1021  30  4.6  24.1 77777 0999999999   7  .089   0  0
 90 12 31 18    0    0    0 ?0    0 ?0    0 ?0  2  2  -2.8  -7.2  72 1022  50  4.1  24.1 77777 0999999999   799999.   0  0
 90 12 31 19    0    0    0 ?0    0 ?0    0 ?0  1  1  -3.3  -6.7  78 1021  50  5.2  24.1 77777 0999999999   799999.   0  0
 90 12 31 20    0    0    0 ?0    0 ?0    0 ?0  1  1  -3.9  -6.7  81 1021  30  4.6  24.1 77777 0999999999   799999.   0  0
 90 12 31 21    0    0    0 ?0    0 ?0    0 ?0  1  1  -3.9  -6.7  81 1021  30  4.1  24.1 77777 0999999999   799999.   0  0
 90 12 31 22    0    0    0 ?0    0 ?0    0 ?0  1  1  -4.4  -6.7  85 1021  30  3.6  24.1 77777 0999999999   799999.   0  0
 90 12 31 23    0    0    0 ?0    0 ?0    0 ?0  1  1  -4.4  -6.7  85 1020  30  3.1  24.1 77777 0999999999   799999.   0  0
 90 12 31 24    0    0 9999 ?0 9999 ?0 9999 ?0 99 99 9999. 9999. 999 9999 9999999.99999.999999 9999999999999999999.9999999
```

A.3 SCRIPT OUTPUT FOR MEMPHIS INTERNATIONAL DATA

Counts and percentages for each (direction, speed) bin are represented in the file content below. Each line represents a single direction bin starting at direction 0° and moving clockwise. On each line are the slash-separated counts and percentages for the direction as a whole and then for each of the six speed bins.

```
# Direction bin values:  0 22.5 45 67.5 90 112.5 135 157.5 180 202.5 225 247.5 270 292.5 315 337.5
# Speed bin values:  2 4 6 8 10
 0: 30447/13.71     14505/6.533     5722/2.577      5838/2.629      3556/1.602      683/0.308       143/0.064
 1: 13027/5.87      580/0.261       5425/2.443      4720/2.126      2000/0.901      271/0.122       31/0.014
 2: 11816/5.32      826/0.372       5560/2.504      4076/1.836      1239/0.558      106/0.048       9/0.004
 3: 10141/4.57      1084/0.488      5538/2.494      2810/1.266      653/0.294       51/0.023        5/0.002
 4: 15396/6.93      2548/1.148      9390/4.229      2825/1.272      559/0.252       56/0.025        18/0.008
 5: 7954/3.58       1073/0.483      4517/2.034      1860/0.838      446/0.201       39/0.018        19/0.009
 6: 12243/5.51      1269/0.572      6267/2.822      3322/1.496      1118/0.504      189/0.085       78/0.035
 7: 16578/7.47      1401/0.631      8091/3.644      4544/2.046      1966/0.885      429/0.193       147/0.066
 8: 30071/13.54     1503/0.677      12949/5.832     9951/4.482      4522/2.037      922/0.415       224/0.101
 9: 16737/7.54      540/0.243       5953/2.681      5983/2.695      3375/1.520      707/0.318       179/0.081
10: 14460/6.51      832/0.375       6130/2.761      4537/2.043      2456/1.106      431/0.194       74/0.033
11: 10178/4.58      689/0.310       4448/2.003      3240/1.459      1442/0.649      267/0.120       92/0.041
12: 9555/4.30       810/0.365       4152/1.870      2666/1.201      1415/0.637      359/0.162       153/0.069
13: 7520/3.39       464/0.209       2843/1.280      2220/1.000      1409/0.635      450/0.203       134/0.060
14: 8223/3.70       384/0.173       2388/1.075      2610/1.175      2104/0.948      581/0.262       156/0.070
15: 7695/3.47       341/0.154       2390/1.076      2609/1.175      1815/0.817      437/0.197       103/0.046
```

A.4 JAVA PROPERTIES CONVERSION RESULTS

Listed below in two columns is the results of the conversion of the rose file to Java properties format. The generated file has one *key=value* pair per line.

```
0_1=6.533                 180_1=0.677
0_3=2.577                 180_3=5.832
```

```
0_5=2.629
0_7=1.602
0_9=0.308
0_11=0.064
22.5_1=0.261
22.5_3=2.443
22.5_5=2.126
22.5_7=0.901
22.5_9=0.122
22.5_11=0.014
45_1=0.372
45_3=2.504
45_5=1.836
45_7=0.558
45_9=0.048
45_11=0.004
67.5_1=0.488
67.5_3=2.494
67.5_5=1.266
67.5_7=0.294
67.5_9=0.023
67.5_11=0.002
90_1=1.148
90_3=4.229
90_5=1.272
90_7=0.252
90_9=0.025
90_11=0.008
112.5_1=0.483
112.5_3=2.034
112.5_5=0.838
112.5_7=0.201
112.5_9=0.018
112.5_11=0.009
135_1=0.572
135_3=2.822
135_5=1.496
135_7=0.504
135_9=0.085
135_11=0.035
157.5_1=0.631
157.5_3=3.644
157.5_5=2.046
157.5_7=0.885
157.5_9=0.193
157.5_11=0.066
180_5=4.482
180_7=2.037
180_9=0.415
180_11=0.101
202.5_1=0.243
202.5_3=2.681
202.5_5=2.695
202.5_7=1.52
202.5_9=0.318
202.5_11=0.081
225_1=0.375
225_3=2.761
225_5=2.043
225_7=1.106
225_9=0.194
225_11=0.033
247.5_1=0.31
247.5_3=2.003
247.5_5=1.459
247.5_7=0.649
247.5_9=0.12
247.5_11=0.041
270_1=0.365
270_3=1.87
270_5=1.201
270_7=0.637
270_9=0.162
270_11=0.069
292.5_1=0.209
292.5_3=1.28
292.5_5=1
292.5_7=0.635
292.5_9=0.203
292.5_11=0.06
315_1=0.173
315_3=1.075
315_5=1.175
315_7=0.948
315_9=0.262
315_11=0.07
337.5_1=0.154
337.5_3=1.076
337.5_5=1.175
337.5_7=0.817
337.5_9=0.197
337.5_11=0.046
```

B. GRID CALCULATIONS

B.1 CALCULATING CELL SIZE

A grid of width 0.0588638889° longitude and 0.0318777777° latitude with a uniform cell structure in 200 columns and 120 rows is used. The center point of the grid is at latitude 35.0931°. Cell size calculations follow.

$$
\begin{aligned}
R_{earth} &= 6370.949\,km \\
R_{lat} &= cos(\,35.0931\,deg\,\frac{\pi\,rad}{180\,deg}\,)\,R_{earth} \\
&= 5212.831\,km
\end{aligned}
$$

$$
\begin{aligned}
W_{grid} &= 0.0588638889\,deg\,(\frac{\pi\,rad}{180\,deg})\,R_{lat}\,(\frac{1000\,m}{km}) \\
&= 5355.500\,m
\end{aligned}
$$

$$
W_{cell} = \frac{5355.500\,m}{200cells} = \frac{26.777\,m}{cell}
$$

$$
\begin{aligned}
H_{grid} &= 0.0318777777\,deg\,(\frac{\pi\,rad}{180\,deg})\,R_{earth}\,(\frac{1000\,m}{km}) \\
&= 3544.619\,m
\end{aligned}
$$

$$
H_{cell} = \frac{3544.619\,m}{120cells} = \frac{29.538\,m}{cell}
$$

Thus, cell size is roughly 27x30 m.

B.2 CALCULATING NUMBER OF CELLS

Assume you want 25x25 m grid cells at a latitude of 35.08 ° north and a grid width and height of 0.04 ° and 0.03 °, respectively. Using an equatorial earth radius of 6370.949 km, the radius at a latitude of 35.08 is

$$
\cos(\frac{35.08\pi\,rad}{180.0\,deg})\,(6370.949\,km) = 5213.669\,km
$$

Thus, a 0.05 ° grid spread over cells of width 25 m results in a number of cell columns calculated as

$$
0.05\,^{\circ}\,(\frac{\pi\,rad}{180\,^{\circ}})\,(5213.669\,km)\,(\frac{1000\,m}{km})\,(\frac{1\,cell}{25\,m}) = 182\,cells
$$

Similarly, for the number of cell rows, the calculation is

$$
0.03\,^{\circ}\,(\frac{\pi\,^{\circ}}{180\,rad})\,(6370.949\,km)\,(\frac{1000\,m}{km})\,(\frac{1\,cell}{25\,m}) = 134\,cells
$$

C. HPAC CALCULATIONS

C.1 EXAMPLE CALCULATION AND PLOT REQUEST

```
<?xml version="1.0" encoding="UTF-8"?>
<hpac:Request
    xmlns:hpac="http://www.sensornet.gov/snet/hpac"
    xmlns:gml="http://www.opengis.net/gml"
    xmlns:wfs="http://www.opengis.net/wfs">
  <hpac:userName>Memphis01</hpac:userName>
  <hpac:projectName>vertex-1</hpac:projectName>
  <hpac:startTime>2005-03-10T12:00:00Z</hpac:startTime>

<hpac:calculate>
  <hpac:coord>(redacted)</hpac:coord>
  <hpac:fixedWinds>
    <hpac:direction>@direction@</hpac:direction>
    <hpac:speed>@speed@</hpac:speed>
  </hpac:fixedWinds>
  <hpac:project><![CDATA[
URL=file\:/D\:/users/re7/hpac/memphis1.hpac
class=mil.dtra.hpac.data.Project
currentRunTime.class=mil.dtra.hpac.data.Time
currentRunTime=20050302164436000,GMT+00\:00
flags.audit.HPACVersion=HPAC 4.04.011
flags.audit.analyst=
flags.audit.classification=Unclassified
flags.audit.date=
flags.audit.projectTitle=
flags.class=mil.dtra.hpac.data.project.Flags
flags.restartFlag=false
flags.scipuffMethod=dynamic,dense,static,
flags.scipuffMode=
limits.class=mil.dtra.hpac.data.project.Limits
limits.maxGridCellsPerSurface=25000
limits.maxMetHorzSize=1000
limits.maxPuffs=20000
maxTimeStep=30.0
name=vertex-1
objectSet.0.class=mil.dtra.hpac.data.SimpleIncidentOwner
objectSet.0.incident.ID=incident-1109771978576
objectSet.0.incident.availableEffects.class=mil.dtra.hpac.data.AvailableEffects
objectSet.0.incident.availableEffects=
objectSet.0.incident.class=mil.dtra.hpac.data.Incident
objectSet.0.incident.coord=-90.13002014160156,35.08794403076172
objectSet.0.incident.hasCustomMaterials=true
objectSet.0.incident.hasCustomReleases=true
objectSet.0.incident.heavy=false
objectSet.0.incident.location.class=mil.dtra.hpac.data.LLALocation
objectSet.0.incident.location.value=(redacted)
objectSet.0.incident.modelName=Analytical Incident
objectSet.0.incident.modelServiceName=no service
objectSet.0.incident.name=Vertex
objectSet.0.incident.releaseList.0.ID=ContinuousRelease-4605695726944205638
objectSet.0.incident.releaseList.0.buoyancy=0.0,C-m3/sec
objectSet.0.incident.releaseList.0.class=mil.dtra.hpac.data.release.ContinuousRelease
objectSet.0.incident.releaseList.0.distribution=-1
objectSet.0.incident.releaseList.0.dryMassFraction=0.1,value
objectSet.0.incident.releaseList.0.duration=30.0,min
objectSet.0.incident.releaseList.0.horzSize=50.0,km
objectSet.0.incident.releaseList.0.horzUncertainty=0.0,m
objectSet.0.incident.releaseList.0.incidentID=incident-1109771978576
objectSet.0.incident.releaseList.0.location.class=mil.dtra.hpac.data.LLALocation
objectSet.0.incident.releaseList.0.location.value=(redacted)
objectSet.0.incident.releaseList.0.locationGroup=0
objectSet.0.incident.releaseList.0.massMeanDiameter=0.0001,m
objectSet.0.incident.releaseList.0.massRate=(redacted),units/sec
objectSet.0.incident.releaseList.0.massSigma=1.1,value
objectSet.0.incident.releaseList.0.material.CASNumber=N/A
objectSet.0.incident.releaseList.0.material.ID=place holder
objectSet.0.incident.releaseList.0.material.UNnumber=N/A
objectSet.0.incident.releaseList.0.material.agentType=C&I
objectSet.0.incident.releaseList.0.material.antoineCoeffs=7.0147,892.52,249.69,
objectSet.0.incident.releaseList.0.material.bins=0.0,1.25E-5,1.693402E-5,2.294088E-5,3.107851E-5,4.210272E-5,5.703746E-5,\
7.726986E-5,1.046792E-4,1.41811E-4,1.921146E-4,2.602616E-4,3.525821E-4,4.776503E-4,6.470835E-4,8.766174E-4,\
0.001187573,0.00160883,0.002179517,0.002952637,0.0040,
objectSet.0.incident.releaseList.0.material.class=mil.dtra.hpac.material.data.LiquidMaterial
objectSet.0.incident.releaseList.0.material.effAvail=0
objectSet.0.incident.releaseList.0.material.effClass=0
objectSet.0.incident.releaseList.0.material.gasDensity=2.98799991607666
objectSet.0.incident.releaseList.0.material.gasDepVelocity=0.0
objectSet.0.incident.releaseList.0.material.liquidDensity=1471.3,-0.4179,
objectSet.0.incident.releaseList.0.material.longName=Liquid Chlorine
objectSet.0.incident.releaseList.0.material.maxDayDecay=0.0
objectSet.0.incident.releaseList.0.material.minNightDecay=0.0
objectSet.0.incident.releaseList.0.material.minPuffConcentration=0.0
```

```
objectSet.0.incident.releaseList.0.material.molecularWeight=70.90599822998047
objectSet.0.incident.releaseList.0.material.name=cl2_liq
objectSet.0.incident.releaseList.0.material.nwpnDecay=0.0
objectSet.0.incident.releaseList.0.material.savedFields=15
objectSet.0.incident.releaseList.0.material.secondaryEvapFlag=true
objectSet.0.incident.releaseList.0.material.spreadFactor=3.5
objectSet.0.incident.releaseList.0.material.supplementalProps.class=mil.dtra.hpac.material.data.SupplementalPropsArray
objectSet.0.incident.releaseList.0.material.surfaceTension=0.017330000177025795
objectSet.0.incident.releaseList.0.material.typeMask=1048580
objectSet.0.incident.releaseList.0.material.units=kg
objectSet.0.incident.releaseList.0.material.viscosity=3.8499999209307134E-4
objectSet.0.incident.releaseList.0.materialCustomized=true
objectSet.0.incident.releaseList.0.momentum=0.0,m4/s2
objectSet.0.incident.releaseList.0.probArrival=1.0
objectSet.0.incident.releaseList.0.puffDuration=4.0,hr
objectSet.0.incident.releaseList.0.sigmaY=1.0,m
objectSet.0.incident.releaseList.0.sigmaZ=1.0,m
objectSet.0.incident.releaseList.0.startTime.class=mil.dtra.hpac.data.Time
objectSet.0.incident.releaseList.0.startTime=20050302135938000,GMT+00\:00
objectSet.0.incident.releaseList.0.statusMap.class=mil.dtra.hpac.data.release.StatusMap
objectSet.0.incident.releaseList.0.statusMap=buoyancy\:1,releaseStatus\:5,sigmaZ\:1,massMeanDiameter\:1,horzUncertainty\:1,\
horzSize\:1,vertSize\:1,material\:5,dryMassFraction\:5,vertUncertainty\:1,massSigma\:1,massRate\:5,\
momentum\:1,puffDuration\:1,distribution\:5,startTime\:1,location\:5,sigmaY\:1,duration\:1,
objectSet.0.incident.releaseList.0.vertSize=2500.0,m
objectSet.0.incident.releaseList.0.vertUncertainty=0.0,m
objectSet.0.incident.releaseList.class=mil.dtra.hpac.data.release.ReleaseList
objectSet.0.incident.startTime.class=mil.dtra.hpac.data.Time
objectSet.0.incident.startTime=20050302135938000,GMT+00\:00
objectSet.0.modelIncident.class=mil.dtra.hpac.data.EmptyModelIncident
objectSet.0.modelIncident=empty model incident
objectSet.0.notes=
objectSet.0.showMapIconsFlag=true
objectSet.class=mil.dtra.hpac.data.ObjectSet
options.adaptiveGridMinSize=9.999999616903162E35
options.class=mil.dtra.hpac.data.project.Options
options.gridResolution=2
options.puffMinMass=1.0E-20
options.samplerLocations.class=mil.dtra.hpac.data.LargeString
options.samplerLocations.lineCount=0
options.samplerMinOutputInterval=9.999999616903162E35
options.substrateIndex=0
options.surfaceDoseHeight=0.0
options.tropoAvgEnergyDissipationRate=4.0E-4
options.tropoVertLengthScale=10.0
options.tropoVertVelocityVariance=0.01
options.turbDiffusiveAvgTime=9.999999616903162E35
options.turbLightWindScale=1000.0
options.turbLightWindValue=0.25
options.turbVertGridPointCount=11
outputInterval=9.999999616903162E35
serverProjectName=memphis1
spatialDomain.class=mil.dtra.hpac.data.project.SpatialDomain
spatialDomain.computeDefaultFlag=true
spatialDomain.horizontalResolution=9.999999616903162E35
spatialDomain.northEast.class=mil.dtra.hpac.data.LLALocation
spatialDomain.northEast.value=0.0,0.0,2500.0,236
spatialDomain.southWest.class=mil.dtra.hpac.data.LLALocation
spatialDomain.southWest.value=0.0,0.0,0.0,236
spatialDomain.verticalResolution=9.999999616903162E35
swiftFlag=false
temporalDomain.class=mil.dtra.hpac.data.project.TemporalDomain
temporalDomain.computeDefaultFlag=true
temporalDomain.endTime.class=mil.dtra.hpac.data.Time
temporalDomain.endTime=20050303135742000,GMT+00\:00
temporalDomain.startTime.class=mil.dtra.hpac.data.Time
temporalDomain.startTime=20050302135742000,GMT+00\:00
toolDataFiles.RIPDFiles.length=0
toolDataFiles.class=mil.dtra.hpac.data.project.ToolDataFiles
toolDataFiles.populationFiles.length=0
toolDataFiles.postureFile=deferred
toolDataFiles.protectionFile=deferred
valid=true
version=4.1
weather.class=mil.dtra.weather.shared.data.WxWeather
weatherMetBL_BLMethod=128
weatherMetBL_CanopyFlowIndex=2.0
weatherMetBL_CanopyHeight=30.0
weatherMetBL_CloudFraction=0.45
weatherMetBL_DayMaxInversionHeight=1000.0
weatherMetBL_DayMaxSurfaceHeatFlux=50.0
weatherMetBL_NightMaxInversionHeight=50.0
weatherMetBL_NightMaxSurfaceHeatFlux=0.0
weatherMetBL_SurfaceAlbedo=0.16
weatherMetBL_SurfaceBowenRatio=1.5
weatherMetBL_SurfaceMoisture=2
weatherMetBL_SurfaceRoughness=-1.0E36
weatherMetFlags_DoHazard=0
weatherMetFlags_DoMassConst=true
```

```
weatherMetFlags_DoOutput=0
weatherMetFlags_OutputInterval=1.0E36
weatherMetFlags_TimeRef=0
weatherMetFlags_UncertaintyScaleLength=100.0
weatherMetLSV_LengthScale=100.0
weatherMetLSV_Method=128
weatherMetLSV_Turb=0.0
weatherMetMet_FixedWindsDirection=202.5
weatherMetMet_FixedWindsSpeed=6.5
weatherMetMet_Input.length=0
weatherMetMet_MaxProfileLocations=65535
weatherMetMet_MaxSurfaceLocations=65535
weatherMetMet_MetFile1.class=mil.dtra.hpac.server.fileutils.FileReference
weatherMetMet_MetFile1=deferred
weatherMetMet_MetFile2.class=mil.dtra.hpac.server.fileutils.FileReference
weatherMetMet_MetFile2=deferred
weatherMetMet_MetMethod=448
#weatherMetMet_MetMethod=1
weatherMetMet_NumberSurfClimoStations=0
weatherMetMet_TimeBin=3600.0
weatherMetMet_UACDMonthDay=301
weatherMetMet_WindDirectionUnit=1
weatherMetMet_WindSpeedUnit=1
weatherMetPrecip_PrecipClass=0
weatherMetPrecip_PrecipType=0
weatherTerrainMC_ErrorCriteria=0.01,1.0E-5,
weatherTerrainMC_MaxIterations=200,100,
weatherTerrainMC_NumberVerticalPoints=23
weatherTerrainMC_SwiftDeltaT=1.0E36
weatherTerrainMC_VerticalAdjustment=0.01,1.0,
weatherTerrainMC_VerticalGrid=50.0,150.0,261.43,385.414,523.165,675.995,845.317,1032.65,1239.62,1467.99,\
1719.6,1996.44,2300.62,2634.36,3000.0,3400.0,3892.62,4503.54,5266.7,6227.12,7444.83,9000.0,11000.0,
weatherTerrain_MCType=57858
weatherTerrain_TerrainFile.class=mil.dtra.hpac.server.fileutils.FileReference
weatherTerrain_TerrainFile=clientPath,/home/re7/src/snet2-dev/memphis/memphis1.ter
weatherVersion=2
weatherWeather_DefaultWeather=10
weatherWeather_LocalSurfaceType=Read terrain file
weatherWeather_LocalWeatherSource=-5
wxSpatialDomain.class=mil.dtra.hpac.data.project.SpatialDomain
wxSpatialDomain.computeDefaultFlag=true
wxSpatialDomain.horizontalResolution=9.999999616903162E35
wxSpatialDomain.northEast.class=mil.dtra.hpac.data.LLALocation
wxSpatialDomain.northEast.value=(redacted)
wxSpatialDomain.southWest.class=mil.dtra.hpac.data.LLALocation
wxSpatialDomain.southWest.value=(redacted)
wxSpatialDomain.verticalResolution=9.999999616903162E35
wxTemporalDomain.class=mil.dtra.hpac.data.project.TemporalDomain
wxTemporalDomain.computeDefaultFlag=true
wxTemporalDomain.endTime.class=mil.dtra.hpac.data.Time
wxTemporalDomain.endTime=20050302182938000,GMT+00\:00
wxTemporalDomain.startTime.class=mil.dtra.hpac.data.Time
wxTemporalDomain.startTime=20050302135938000,GMT+00\:00
]]></hpac:project>
</hpac:calculate>

<hpac:plot>
  <hpac:category>Surface</hpac:category>
  <hpac:class>Surface Dosage</hpac:class>
  <hpac:choice>cl2_liq</hpac:choice>
  <hpac:kind>Total</hpac:kind>
  <hpac:timeID>surface</hpac:timeID>
  <hpac:plotData></hpac:plotData>
  <hpac:plotType>mean</hpac:plotType>
  <hpac:plotTypeValue>0.0</hpac:plotTypeValue>
  <hpac:hazardFlag>true</hpac:hazardFlag>
  <hpac:contourScale>16667.0</hpac:contourScale>
  <hpac:contourUnits>mg-min/m3</hpac:contourUnits>
  <hpac:contourElements>
    <hpac:contour>
      <hpac:label>TEEL-0-15m</hpac:label>
      <hpac:value>21.75</hpac:value>
      <hpac:population>0.0</hpac:population>
    </hpac:contour>
    <hpac:contour>
      <hpac:label>TEEL-1-15m</hpac:label>
      <hpac:value>43.5</hpac:value>
      <hpac:population>0.0</hpac:population>
    </hpac:contour>
    <hpac:contour>
      <hpac:label>TEEL-2-15m</hpac:label>
      <hpac:value>130.5</hpac:value>
      <hpac:population>0.0</hpac:population>
    </hpac:contour>
    <hpac:contour>
      <hpac:label>TEEL-3-15m</hpac:label>
      <hpac:value>870.0</hpac:value>
      <hpac:population>0.0</hpac:population>
```

```
    </hpac:contour>
    <hpac:contour>
      <hpac:label>ICt5</hpac:label>
      <hpac:value>1400.0</hpac:value>
      <hpac:population>0.0</hpac:population>
    </hpac:contour>
    <hpac:contour>
      <hpac:label>ICt50</hpac:label>
      <hpac:value>3000.0</hpac:value>
      <hpac:population>0.0</hpac:population>
    </hpac:contour>
    <hpac:contour>
      <hpac:label>LCt50</hpac:label>
      <hpac:value>19000.0</hpac:value>
      <hpac:population>0.0</hpac:population>
    </hpac:contour>
  </hpac:contourElements>
</hpac:plot>
</hpac:Request>
```

C.2 BATCH EXECUTION SCRIPT

The command-line Java HPAC client is executed in a script named *ProjectRequestionHandler.run.sh*, invoked inside the inner for-loop. Note the threat name passed as the parameter to the batch execution script specifies files whose names have extensions *.req.xml* and *.out.xml*. The former is the file containing the request document for input, and the latter names the result file.

```
#!/bin/sh -a
#------------------------------------------------------------------------
#       NAME:           Batch.run.sh                                    -
#       PURPOSE:                                                        -
#               Run a batch of cases                                    -
#       USAGE:                                                          -
#               $ Batch.run.sh threat-name                              -
#------------------------------------------------------------------------

if [ $# -lt 1 ]; then
  threat=vertex-1
else
  threat=$1
fi

dirs="0 22.5 45 67.5 90 112.5 135 157.5 180 202.5 225 247.5 270 292.5 315 337.5"
speeds="1 3 5 7 9 11"

if [ ! -d $threat ]; then
  mkdir $threat
fi
echo "*** Threat: ${threat} ***"
echo "Starting at: ‘date +%Y-%m-%dT%H:%M:%S%Z‘"

for dir in $dirs; do
  echo ""
  echo ""
  echo "Direction: $dir"

  for speed in $speeds; do
    case_name="${threat}.${dir}_${speed}"
    req_name=${case_name}.req.xml
    out_name=${case_name}.out.xml
    echo "Case: $dir - $speed"

    sed \
        -e "s/@direction@/$dir/g" -e "s/@speed@/$speed/g" \
        ${threat}.req.xml > ${threat}/${req_name}
    ProjectRequestHandler.run.sh \
        -request ${threat}/${req_name} \
        > ${threat}/${out_name}
  done
done

echo ""
echo "Finished at: ‘date +%Y-%m-%dT%H:%M:%S%Z‘"
```

C.3 EXAMPLE MODEL OUTPUT

```
<?xml version="1.0" encoding="UTF-8"?>
<hpac:Response
```

```
    xmlns:hpac="http://www.sensornet.gov/snet/hpac"
    xmlns:gml="http://www.opengis.net/gml"
    xmlns:wfs="http://www.opengis.net/wfs">
  <hpac:calculationStatus>success</hpac:calculationStatus>
.
.
.
  <wfs:FeatureCollection
      gml:id="Memphis01-vertex-1-1"
      name="Memphis01 Surface Dosage cl2_liq Total  67 min">
    <gml:description>Surface Dosage cl2_liq Total at 67 min</gml:description>
    <gml:boundedBy>
      <gml:Box srsName="http://www.opengis.net/gml/srs/epsg.xml#4326">
        <gml:coordinates>
-90.68607330322266,35.07038116455078 -90.13958740234375,35.09679412841797
        </gml:coordinates>
      </gml:Box>
    </gml:boundedBy>
    <gml:TimePeriod>
      <gml:begin>
        <gml:TimeInstant>
          <gml:timePosition>2005-03-11T00:48:29.996Z</gml:timePosition>
        </gml:TimeInstant>
      </gml:begin>
      <gml:end>
        <gml:TimeInstant>
          <gml:timePosition>2005-03-11T01:21:58.995Z</gml:timePosition>
        </gml:TimeInstant>
      </gml:end>
    </gml:TimePeriod>
    <gml:featureMember>
      <hpac:contour>
        <hpac:label>TEEL-0-15m</hpac:label>
        <hpac:value>0.0013049738</hpac:value>
        <hpac:population>260.77588</hpac:population>
      </hpac:contour>
      <gml:location>
        <gml:polygon>
          <gml:exterior>
            <gml:LinearRing>
              <gml:coordinates decimal="." cs="," ts=" ">
-90.68607330322266,35.070762634277344 -90.68607330322266,35.07306671142578 &#xD;
-90.68607330322266,35.08009338378906 -90.68607330322266,35.087120056152344 &#xD;
...
              </gml:coordinates>
            </gml:LinearRing>
          </gml:exterior>
          <gml:interior>
            <gml:LinearRing>
              <gml:coordinates decimal="." cs="," ts=" ">
-90.68607330322266,35.079689025878906 -90.68607330322266,35.08009338378906 &#xD;
-90.68607330322266,35.087120056152344 -90.68607330322266,35.08751678466797 &#xD;
...
              </gml:coordinates>
            </gml:LinearRing>
          </gml:interior>
        </gml:polygon>
      </gml:location>
    </gml:featureMember>
    <gml:featureMember>
      <hpac:contour>
        <hpac:label>TEEL-1-15m</hpac:label>
        <hpac:value>0.0026099477</hpac:value>
        <hpac:population>146.29924</hpac:population>
      </hpac:contour>
      <gml:location>
        <gml:polygon>
          <gml:exterior>
            <gml:LinearRing>
              <gml:coordinates decimal="." cs="," ts=" ">
-90.68607330322266,35.079689025878906 -90.68607330322266,35.08009338378906 &#xD;
-90.68607330322266,35.087120056152344 -90.68607330322266,35.08751678466797 &#xD;
...
              </gml:coordinates>
            </gml:LinearRing>
          </gml:exterior>
          <gml:interior>
            <gml:LinearRing>
              <gml:coordinates decimal="." cs="," ts=" ">
-90.30671691894531,35.08171081542969 -90.30854797363281,35.081851959228516 &#xD;
-90.3084945678711,35.08340072631836 -90.30843353271484,35.08536148071289 &#xD;
...
              </gml:coordinates>
            </gml:LinearRing>
          </gml:interior>
        </gml:polygon>
      </gml:location>
    </gml:featureMember>
```

```
    <gml:featureMember>
      <hpac:contour>
        <hpac:label>TEEL-2-15m</hpac:label>
        <hpac:value>0.007829843</hpac:value>
        <hpac:population>35.580402</hpac:population>
      </hpac:contour>
      <gml:location>
        <gml:polygon>
          <gml:exterior>
            <gml:LinearRing>
              <gml:coordinates decimal="." cs="," ts=" ">
-90.30671691894531,35.08171081542969 -90.30854797363281,35.081851959228516 &#xD;
-90.3084945678711,35.08340072631836 -90.30843353271484,35.08536148071289 &#xD;
...
              </gml:coordinates>
            </gml:LinearRing>
          </gml:exterior>
          <gml:interior>
            <gml:LinearRing>
              <gml:coordinates decimal="." cs="," ts=" ">
-90.1688003540039,35.0831413269043 -90.16893005371094,35.083168029785156 &#xD;
-90.16888427734375,35.08393478393555 -90.16887664794922,35.08404541015625 &#xD;
...
              </gml:coordinates>
            </gml:LinearRing>
          </gml:interior>
        </gml:polygon>
      </gml:location>
    </gml:featureMember>
    <gml:featureMember>
      <hpac:contour>
        <hpac:label>TEEL-3-15m</hpac:label>
        <hpac:value>0.052198958</hpac:value>
        <hpac:population>8.54544E-40</hpac:population>
      </hpac:contour>
      <gml:location>
        <gml:polygon>
          <gml:exterior>
            <gml:LinearRing>
              <gml:coordinates decimal="." cs="," ts=" ">
-90.1688003540039,35.0831413269043 -90.16893005371094,35.083168029785156 &#xD;
-90.16888427734375,35.08393478393555 -90.16887664794922,35.08404541015625 &#xD;
...
              </gml:coordinates>
            </gml:LinearRing>
          </gml:exterior>
          <gml:interior>
            <gml:LinearRing>
              <gml:coordinates decimal="." cs="," ts=" ">
-90.16023254394531,35.0831298828125 -90.16047668457031,35.083168029785156 &#xD;
-90.16043853759766,35.083797454833984 -90.1604232788086,35.08404541015625 &#xD;
...
              </gml:coordinates>
            </gml:LinearRing>
          </gml:interior>
        </gml:polygon>
      </gml:location>
    </gml:featureMember>
    <gml:featureMember>
      <hpac:contour>
        <hpac:label>ICt5</hpac:label>
        <hpac:value>0.08399832</hpac:value>
        <hpac:population>0.0</hpac:population>
      </hpac:contour>
      <gml:location>
        <gml:polygon>
          <gml:exterior>
            <gml:LinearRing>
              <gml:coordinates decimal="." cs="," ts=" ">
-90.16023254394531,35.0831298828125 -90.16047668457031,35.083168029785156 &#xD;
-90.16043853759766,35.083797454833984 -90.1604232788086,35.08404541015625 &#xD;
...
              </gml:coordinates>
            </gml:LinearRing>
          </gml:exterior>
          <gml:interior>
            <gml:LinearRing>
              <gml:coordinates decimal="." cs="," ts=" ">
-90.15310668945312,35.08338165283203 -90.15312194824219,35.0833854675293 &#xD;
-90.15310668945312,35.08359909057617 -90.15309143066406,35.08382797241211 &#xD;
...
              </gml:coordinates>
            </gml:LinearRing>
          </gml:interior>
        </gml:polygon>
      </gml:location>
    </gml:featureMember>
    <gml:featureMember>
```

```
      <hpac:contour>
        <hpac:label>ICt50</hpac:label>
        <hpac:value>0.1799964</hpac:value>
        <hpac:population>0.0</hpac:population>
      </hpac:contour>
      <gml:location>
        <gml:polygon>
          <gml:exterior>
            <gml:LinearRing>
              <gml:coordinates decimal="." cs="," ts=" ">
-90.15310668945312,35.08338165283203 -90.15312194824219,35.0833854675293 &#xD;
-90.15310668945312,35.08359909057617 -90.15309143066406,35.08382797241211 &#xD;
...
              </gml:coordinates>
            </gml:LinearRing>
          </gml:exterior>
          <gml:interior>
            <gml:LinearRing>
              <gml:coordinates decimal="." cs="," ts=" ">
-90.1451187133789,35.08300018310547 -90.14517974853516,35.08305740356445 &#xD;
-90.14522552490234,35.083106994628906 -90.14527130126953,35.08315658569336 &#xD;
...
              </gml:coordinates>
            </gml:LinearRing>
          </gml:interior>
        </gml:polygon>
      </gml:location>
    </gml:featureMember>
    <gml:featureMember>
      <hpac:contour>
        <hpac:label>LCt50</hpac:label>
        <hpac:value>1.1399772</hpac:value>
        <hpac:population>0.0</hpac:population>
      </hpac:contour>
      <gml:location>
        <gml:polygon>
          <gml:exterior>
            <gml:LinearRing>
              <gml:coordinates decimal="." cs="," ts=" ">
-90.1451187133789,35.08300018310547 -90.14517974853516,35.08305740356445 &#xD;
-90.14522552490234,35.083106994628906 -90.14527130126953,35.08315658569336 &#xD;
...
              </gml:coordinates>
            </gml:LinearRing>
          </gml:exterior>
        </gml:polygon>
      </gml:location>
    </gml:featureMember>
  </wfs:FeatureCollection>
</hpac:Response>
```

D. DISCRETE SENSOR LOCATION SELECTION

Grid matching consists of reading a set of allowed or possible sensor locations and processing them against a resulting grid file. The Port of Memphis specified 29 locations. Output from the script is the location list in descending priority order, one per line. Each line specifies the location identifier followed by the cell column and row containing the location and finally the cumulative risk value in the cell for the iteration.

D.1 PORT OF MEMPHIS FIRST ITERATION RESULTS

```
11      84, 25 ->  124600.00
10      83, 27 ->  122400.00
12      93, 35 ->  119800.00
21     142, 89 ->  118500.00
13     101, 38 ->  116800.00
22     145, 89 ->  115600.00
14     102, 28 ->  113300.00
25     158, 89 ->  110700.00
20     138, 87 ->  109600.00
```

```
15    107, 46 ->  108600.00
23    152, 96 ->  108200.00
24    156, 98 ->  106300.00
09     79, 37 ->  104300.00
08     75, 36 ->  103400.00
26    167, 99 ->  101200.00
19    133, 81 ->   97390.00
16     94, 51 ->   96840.00
07     69, 22 ->   96780.00
01     21, 28 ->   90870.00
29    124, 90 ->   86440.00
02     27, 25 ->   85700.00
18    118, 66 ->   83390.00
03     32, 36 ->   83340.00
27    155,109 ->   83210.00
28    148,106 ->   82920.00
06     63, 31 ->   77780.00
04     42, 22 ->   74760.00
05     61, 19 ->   71750.00
17    109, 77 ->   71210.00
```

D.2 PORT OF MEMPHIS SECOND ITERATION RESULTS

```
21    142, 89 ->   74300.00
22    145, 89 ->   71790.00
25    158, 89 ->   67520.00
23    152, 96 ->   65440.00
20    138, 87 ->   65170.00
24    156, 98 ->   63910.00
26    167, 99 ->   59370.00
19    133, 81 ->   50090.00
27    155,109 ->   46170.00
28    148,106 ->   45560.00
29    124, 90 ->   41240.00
01     21, 28 ->   36980.00
02     27, 25 ->   31410.00
03     32, 36 ->   28500.00
04     42, 22 ->   18990.00
18    118, 66 ->   17990.00
17    109, 77 ->   16860.00
15    107, 46 ->   13380.00
13    101, 38 ->   11170.00
16     94, 51 ->   10920.00
12     93, 35 ->   10000.00
05     61, 19 ->    7171.00
14    102, 28 ->    6977.00
06     63, 31 ->    6320.00
09     79, 37 ->    5778.00
07     69, 22 ->    5635.00
08     75, 36 ->    5325.00
10     83, 27 ->    3111.00
```

```
11     84, 25 ->       0.00
```

D.3 PORT OF MEMPHIS THIRD ITERATION RESULTS

```
01     21, 28 ->   32800.00
02     27, 25 ->   27240.00
03     32, 36 ->   24330.00
04     42, 22 ->   15010.00
29    124, 90 ->    4349.00
05     61, 19 ->    4332.00
07     69, 22 ->    3602.00
25    158, 89 ->    3576.00
17    109, 77 ->    2808.00
20    138, 87 ->    2541.00
06     63, 31 ->    2217.00
19    133, 81 ->    1779.00
22    145, 89 ->    1060.00
10     83, 27 ->     972.20
08     75, 36 ->     893.80
09     79, 37 ->     790.80
26    167, 99 ->     757.00
21    142, 89 ->     318.40
23    152, 96 ->     180.70
18    118, 66 ->     150.40
16     94, 51 ->     133.10
14    102, 28 ->     123.30
15    107, 46 ->     122.90
13    101, 38 ->      50.59
24    156, 98 ->      10.38
12     93, 35 ->       0.49
11     84, 25 ->       0.00
27    155,109 ->       0.00
28    148,106 ->       0.00
```

D.4 PORT OF MEMPHIS FOURTH ITERATION RESULTS

```
25    158, 89 ->    3492.00
20    138, 87 ->    2426.00
29    124, 90 ->    1637.00
19    133, 81 ->    1637.00
22    145, 89 ->     992.70
02     27, 25 ->     828.60
10     83, 27 ->     814.40
08     75, 36 ->     781.30
26    167, 99 ->     689.40
09     79, 37 ->     678.30
21    142, 89 ->     318.40
23    152, 96 ->     180.70
14    102, 28 ->     123.30
06     63, 31 ->     112.20
18    118, 66 ->      58.03
```

```
15    107, 46 ->      51.36
13    101, 38 ->      50.59
17    109, 77 ->      45.08
07     69, 22 ->      14.78
24    156, 98 ->      10.38
05     61, 19 ->       6.99
03     32, 36 ->       5.89
12     93, 35 ->       0.49
16     94, 51 ->       0.49
04     42, 22 ->       0.15
27    155,109 ->       0.00
28    148,106 ->       0.00
11     84, 25 ->       0.00
01     21, 28 ->       0.00
```

D.5 PORT OF MEMPHIS FIFTH ITERATION RESULTS

```
20    138, 87 ->    2400.00
29    124, 90 ->    1637.00
19    133, 81 ->    1637.00
02     27, 25 ->     828.60
10     83, 27 ->     814.40
08     75, 36 ->     781.30
09     79, 37 ->     678.30
14    102, 28 ->     123.30
06     63, 31 ->     112.20
18    118, 66 ->      58.03
15    107, 46 ->      51.36
13    101, 38 ->      50.59
17    109, 77 ->      45.08
07     69, 22 ->      14.78
25    158, 89 ->       7.93
22    145, 89 ->       7.84
05     61, 19 ->       6.99
03     32, 36 ->       5.89
16     94, 51 ->       0.49
12     93, 35 ->       0.49
04     42, 22 ->       0.15
28    148,106 ->       0.00
27    155,109 ->       0.00
23    152, 96 ->       0.00
26    167, 99 ->       0.00
11     84, 25 ->       0.00
21    142, 89 ->       0.00
24    156, 98 ->       0.00
01     21, 28 ->       0.00
```

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