MSFC-614-Paper

Development of a New Data Tool for Computing Launch and Landing Availability With Respect to Surface Weather

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ABSTRACT

The Marshall Space Flight Center Natural Environments Branch has a long history of expertise in the modeling and computation of statistical launch availabilities with respect to weather conditions. Their existing data analysis product, the Atmospheric Parametric Risk Assessment (APRA) tool, computes launch availability given an input set of vehicle hardware and/or operational weather constraints by calculating the climatological probability of exceeding the specified constraint limits. APRA has been used extensively to provide the Space Shuttle program the ability to estimate impacts that various proposed design modifications would have to overall launch availability. The model accounts for both seasonal and diurnal variability at a single geographic location and provides output probabilities for a single arbitrary launch attempt.

Recently, the Shuttle program has shown interest in having additional capabilities added to the APRA model, including analysis of humidity parameters, inclusion of landing site weather to produce landing availability, and concurrent analysis of multiple sites, to assist in operational landing site selection. In addition, the Constellation program has also expressed interest in the APRA tool, and has requested several additional capabilities to address some Constellation-specific issues, both in the specification and verification of design requirements and in the development of operations concepts. The combined scope of the requested capability enhancements suggests an evolution of the model beyond a simple revision process. Development has begun for a new data analysis tool that will satisfy the requests of both programs. This new tool, Probabilities of Atmospheric Conditions and Environmental Risk (PACER), will provide greater flexibility and significantly enhanced functionality compared to the currently existing tool.

MANUSCRIPT

Mission availability is an important characteristic of any space flight program. A vehicle that is never operationally available to support its intended mission is not very useful. Availability, itself, is a combined function of many distinct elements, such as hardware readiness, ground support readiness, design robustness, and ambient environmental conditions during a given mission phase. Availability of space faring vehicles is particularly sensitive to weather during the launch/ascent and the entry/landing phases of mission operations. For example, during the launch phase, weather and atmospheric conditions greatly affect ascent loads and performance, range safety, guidance, navigation, and control, and thermal protection system performance and survivability. During the entry and landing phase, weather impacts vehicle performance, landing accuracy, vehicle survivability and reusability, and crew safety and recovery operations. During the design stage of vehicle development, design engineers need computed weather-related mission availabilities in order to verify functional requirements and to provide adequate design robustness to ensure program success. During operations, mission planners need availabilities in order to maintain adequate safety margins and for purposes of scheduling manifests to minimize expensive scrubs and avoid contingencies. While weather is just one factor in overall mission availability, it is a critical component for the entire life cycle of space flight vehicle design and operation.

The Marshall Space Flight Center Natural Environments Branch (EV44) has a long history of expertise in probabilistic analyses of atmospheric conditions and the modeling and computation of statistical launch availabilities with respect to weather. EV44 supports the entire NASA engineering community by providing subject matter expertise and custom analyses and has provided computations of mission availability for virtually every flight vehicle program since the agencies inception. During the Apollo program, several stand-alone techniques and data analysis tools were developed. Due to computational limitations, the majority of these tools were analytical in nature, and very focused in their objectives. For example, with fairly long and flexible launch windows, the program had considerable ability to "wait-out" adverse conditions, but mission planners none the less required a characterization of the variability of atmospheric conditions in order to adjust vehicle performance parameters and operational procedures and timelines to promote mission success.

During early Space Shuttle design, many of these tools were integrated and formalized into a computational process known as the Mission Analysis Package (MAP). Significant effort went into the development of better datasets to support the analysis. With respect to weather, the Kennedy Space Center (KSC)/ Cape Canaveral Air Force Station (CCAFS) area is arguably the most observed region on earth. However, a large mass of observations needed to be combined into a format that was easily used by the MAP tool. The Space Shuttle was the first space flight vehicle that required ongoing operational planning. The Apollo, Gemini, and Mercury programs were essentially each a series of single-event missions, whereas, the Shuttle was designed for a continuously rotating manifest. As such, availability was a more critical element of the design requirements for the shuttle than for previous vehicles. MAP gave the design engineers a method to verify that program-specified availability targets could be met with the hardware constraints imposed by the design characteristics.

As the Shuttle vehicle became operational, mission planners requested greater fidelity of availability computations, as well as the need to analyze atmospheric parameters that were not available in MAP. Also, ongoing design modifications and enhancements to the vehicle required engineering analyses of the effects of proposed hardware changes to overall program mission availabilities. During the early 1990s, MAP underwent a major evolution and was renamed the Atmospheric Parametric Risk Analysis (APRA) data tool.

APRA has been used extensively and continues to have significant application to Shuttle program engineering studies and mission analysis, and represents the current state of the art in functional weather availability tools.

Functionally, the APRA methodology is straight forward, and can be described by three separate processes. First, the user enters a list of specific vehicle performance constraints. For example, if a given design element is sensitive to surface winds greater than, say, 15 m/s from a southerly direction (180 degrees), these limits are entered as constraint thresholds. Secondly, APRA reads a user-specified climatology of weather observations for a single geographic site of interest, and groups the data by month and hour of the day. Thirdly, for each month/hour grouping, APRA counts the number of observations where any or all of the input constraints are violated and divides this by the total number of observations in that particular month/hour group. The resulting value, is the probability that an arbitrary observation during the given month and hour of the day will violate the specified constraints. Typically, the probabilities are reported in percentages, and the program includes the capability to convert these "no-go" probabilities to "go" probabilities by the simple transformation P_{go}(in %) = 100 - P_{nogo}(%). The probability of go, P_{go} is what is referred to as weather availability.

The partitioning of the data into monthly groups allows the analysis of seasonal variability, and the partitioning into hour of day groups allows the analysis of diurnal variability. It has been occasionally been asked if the tool can identify probabilities for specific dates, say June 6. However, the available data do not support such fine partitioning. For a 50-year dataset, the set of all June 6 observations will, generally, have greater statistical variability than the larger set of all June observations. Thus, to report availabilities for specific dates will result in less statistically significant answers than by grouping all June days together. APRA is capable of analyzing any or all of the atmospheric parameters given in Table 1. While APRA has enjoyed great success, there are capabilities that have been requested by the NASA engineering community that are currently not implemented. A major upgrade to APRA is being developed to address these additional capabilities and also to increase run-time flexibility. A sampling of these new capabilities, along with potential application, includes the following.

Numerous requests have been received to perform availability analysis with respect to atmospheric humidity. While many in-house datasets do include moisture variables, humidity is not currently implemented in APRA. One application where this would be useful is in determining the probability of iceball growth on the Shuttle External Tank (ET). The ET engineers have requested the probability of encountering a set of ambient conditions that were determined, through chamber testing, to support iceball growth on small existing foam defects. The set of conditions given includes a range of relative humidities. The computation of the requested probabilities was fairly laborious, but would have been simple had humidity been previously implemented. The characterization of iceball growth is an ongoing concern, and the new update will be able to perform such calculations without the user needing to perform custom analyses to support the engineers and the program decision makers.

Table 1. Atmospheric parameters currently implemented in APRA.

Parameter	Units
Minimum cloud ceiling	ft or m
Minimum visibility	nm or km
Minimum sky cover	tenths
Minimum temperature	C or F
Maximum temperature	C or F
Maximum wind speed, by direction	kt or m/s
Presence of lightning within specified radius	nm or km
Presence of thunderstorms in area	yes/no
Presence of precipitation in area	yes/no

The Constellation program has expressed potential interest in maintaining a multiple site network of CONUS landing zones for the Orion crew capsule. No single site will be available for all lunar return trajectories, and, as the capsule will be on a "hot" trajectory, with no orbital staging, an anytime return requirement demands multiple landing sites to accommodate all returns. The program desires very high landing availabilities, but wants to balance the increased availability that multiple site networks will produce with the significant life cycle cost increase that larger network configurations represent. The update will allow easy specification of multi-site network availabilities and allow decision makers to look at how overall availabilities vary with network configuration. In this way, the list of potential sites can be down selected to provide high availabilities with minimal cost.

The Constellation program is also currently investigating the potential use of oceanic landing zones. While oceanic landings have some advantages over ground surface landing, they require much additional environmental characterizations for the design engineers. Wave height and slope are important parameters that must be designed for to ensure the splashdown impact is survivable both for the crew and the vehicle itself. Additionally, sea state affects recovery operations and accessibility. In addition, sea surface temperature is important for crew health from landing through recovery. As such. The program has requested the capability to include oceanic landing zone sea state characterization to the availability analysis. Climatological data over the ocean is very sparse, however. Modeled data of sea surface conditions from several potential landing zones is currently being formatted for inclusion as separate nodes in the multi-site network analysis. The data is being spot verified, where possible, from ocean buoy data, in addition to the verification that has already been performed by the model development organizations. Once completed, this process will allow the addition of oceanic zones to the potential ground based sites, and the two can be used interchangeably in subsequent availability computations.

Several other new capabilities are planned for development. The tool will be implemented using a graphical user interface (GUI) instead of the current namelist methodology. The user will be able to perform multi-case queuing to support automated sensitivity analysis. While some unit conversion capability is available in APRA now, this capability will be greatly enhanced. Distinct engineering disciplines traditionally use unit systems that are most appropriate to their particular interest. The natural Environments Branch receives requests for analysis by groups wanting to express constraints in various unit systems and currently, the user must manipulate these by hand into those that APRA can process. The update will integrate this process seamlessly and greatly reduce the amount of pre- and post-processing necessary to support our customers in their customary unit systems. The final product will also provide greater ability to provide graphical and tabular outputs into easily customizable formats. And finally, the capability to quickly add new observations, environmental parameters, and data sites with minimal effort on the user will be included. The new data tool will be implemented in a scripting language to reduce IO overhead for successive run executions.

As this development represents a significant advancement over the current APRA model, it is being treated more like an evolution than an update. Many of the individual processing routines have been written and tested. The primary remaining task is to integrate all segments into a cohesive framework and implement them in a flexible GUI. This is not, however, a formal software development project. The work is progressing between customer priorities on an "as time permits" basis. The new data tool is tentatively named Probabilities of Atmospheric Conditions and Atmospheric Risk (PACER). The targeted completion date is the Summer of 2008.

mSFC-614-Presentation

Development of a New Data Tool for Computing Launch and Landing Availability With Respect to Surface Weather

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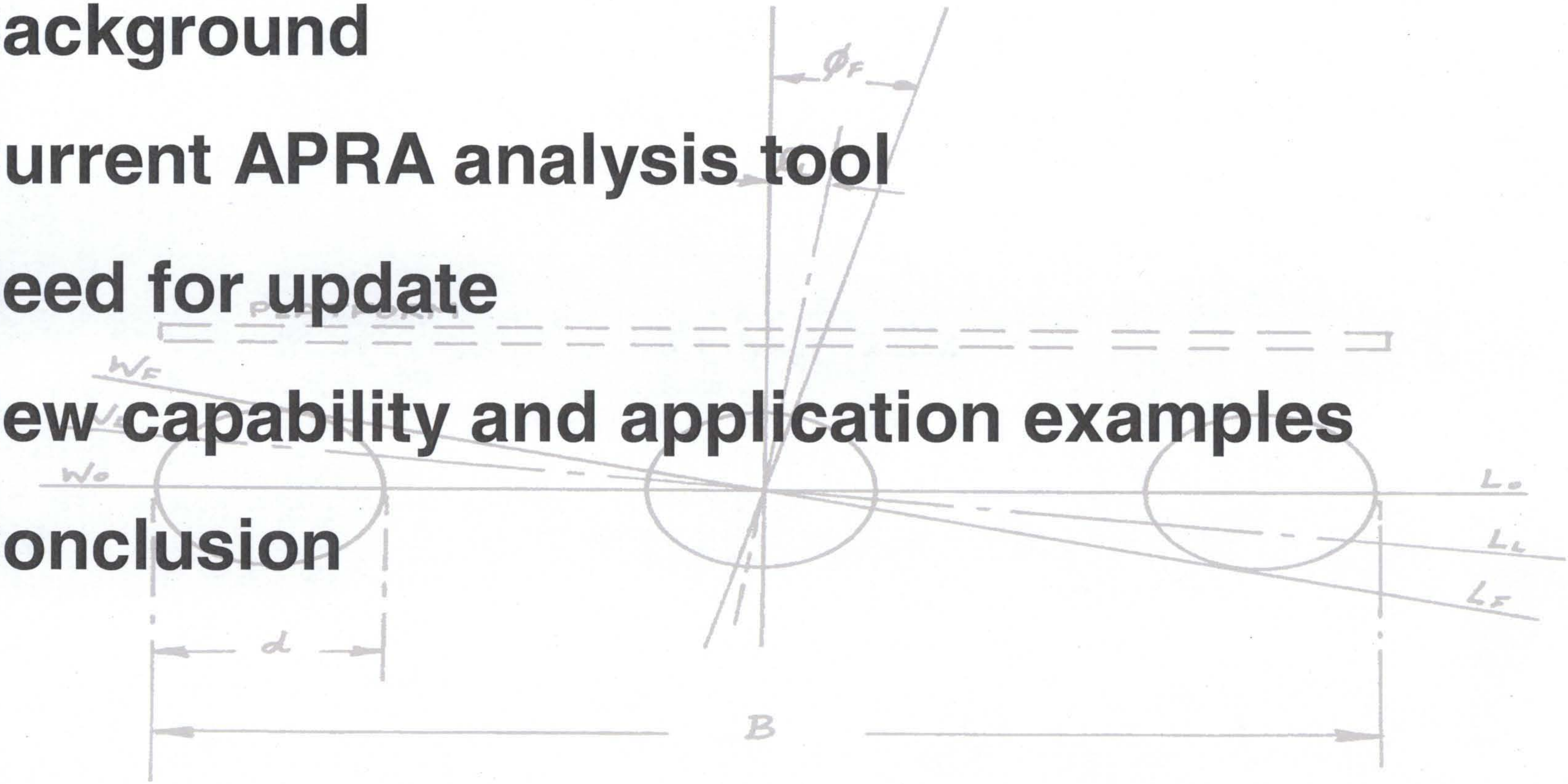
The Ubiquitous Outline

- Background
- Current APRA analysis tool
- Need for update
- New capability and application examples
- Conclusion



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Need for Weather Availability Tool

Weather impacts design/operational constraints

- During launch phase
  - Ascent loads and performance
  - Range safety
  - Guidance, navigation and control
  - Thermal protection systems

- During landing phase
  - Vehicle performance
  - Crew safety and recovery operations
  - Vehicle survivability/reusability
  - Landing accuracy

A vehicle that is never available due to weather constraints is not very useful

- Design engineers need computed weather-related launch availabilities in order to verify functional requirements.
- Mission planners need availabilities to optimize mission success and maintain adequate safety margins.

History

The Marshall Space Flight Center Natural Environments Branch has a long history of expertise in probabilistic analyses of atmospheric conditions and computing launch and landing availabilities with respect to weather

- **Apollo program** – Several stand-alone techniques and analysis tools were developed and used successfully.
- **Early Shuttle design** – Existing methods were integrated and formalized as Mission Analysis Package (MAP). MAP made significant contribution to development and verification of launch constraints and availability.
- **Shuttle mission planning and design modification analysis** – MAP was upgraded with new capabilities and greater usability. New tool was named Atmospheric Parametric Risk Assessment (APRA). APRA has been used extensively to support numerous engineering analyses.

What APRA does

APRA computes the probability that weather conditions will/will not violate a set of specified operational constraints

- Reads a climatological time series of hourly operational weather observations taken at a given site.
- Groups the observations by month and time of day.
- Reads user-specified set of weather constraint thresholds.
- For each time interval bin, computes the probability that an arbitrary measurement will exceed the given constraints.
- Can analyze multiple constraints individually or in combination.
- Provides geographically specific, single-site analysis.

$$P = \frac{\text{Number of constraint violations}}{\text{Total number of observations in group}}$$

Constraint Variables

APRA can check any or all of the following surface conditions

- Minimum cloud ceiling
- Minimum visibility
- Minimum sky cover
- Maximum/minimum temperature
- Maximum wind speed, by direction
- Presence of thunderstorms in area
- Lightning within specified radius
- Presence of precipitation in area

- *** CONSTRAINTS ***
- No Thunderstorms
- No Precipitation
- Visibility >= 5.0 nm
- Cloud Ceiling > 8000.0 ft
- Head Wind <= 25.0 kts
- Tail Wind <= 10.0 kts
- Cross Wind <= 15.0 kts
- Wind Type =PEAK
- Approach From = 155.0 and 335.0
- Liftoff ground wind
- WD(deg) WS(kts)
- 0-139 31.0
- 140-149 28.0
- 150-159 26.0
- 160-169 24.0
- 170-199 22.0
- 200-209 24.0
- 210-219 26.0
- 220-225 28.0
- 226-360 31.0

Period of Record 1957 - 2001 Approach From 155.0 and 335.0	NOGO Probabilities in Percent																							
Local Standard Time (hour)	0	1	2	3	4	5	6	7	8	9	10	11	12	13										
Constraint/Requirement																								
Thunderstorm	0	1	0	0	1	0	1	0	0	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1
Precipitation	7	7	6	7	7	7	8	9	9	8	8	5	6	6	6	6	6	7	6	7	7	8	8	7
Temperature < 40.0 deg F OR Temperature > 100.0 deg F	4	4	4	4	5	5	6	7	4	1	1	0	0	0	0	0	0	0	0	0	1	2	3	3
Liftoff ground wind	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0
Any of the Above	11	12	11	11	12	12	14	16	14	10	9	6	7	7	7	7	7	7	6	8	9	10	11	10
# Times Any Criteria Violated	128	135	128	127	137	142	162	185	157	111	98	72	80	75	76	82	75	84	72	87	101	119	128	117
Total Observations	1147	1157	1158	1155	1154	1152	1159	1171	1160	1137	1142	1139	1129	1136	1146	1144	1152	1166	1148	1156	1164	1137	1154	1150

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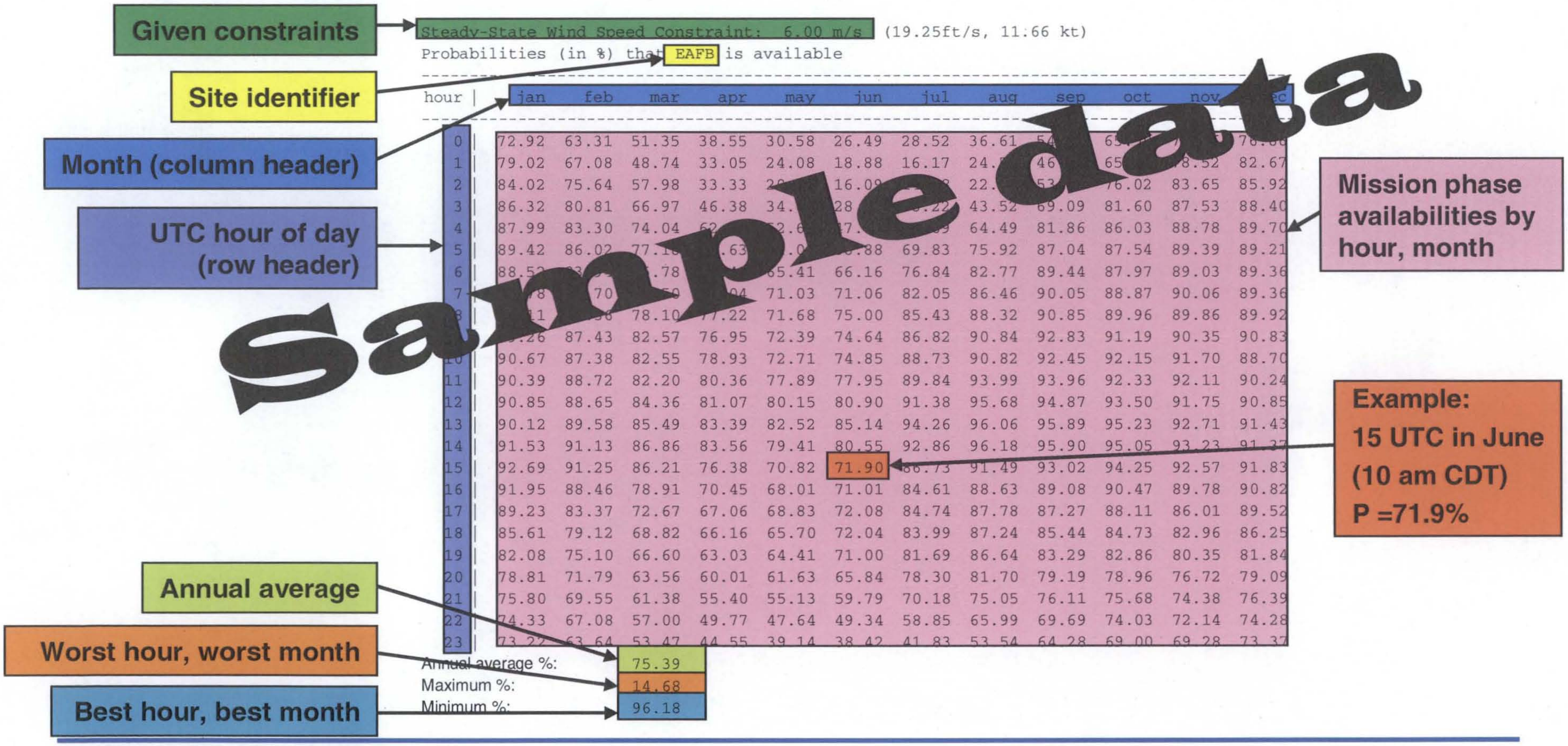
Sample APRA Output Table Format



Given constraints

Site identifier

Month (column header)

UTC hour of day (row header)

Mission phase availabilities by hour, month

Example:
15 UTC in June
(10 am CDT)
P =71.9%

Annual average

Worst hour, worst month

Best hour, best month

```
Steady-State Wind Speed Constraint:  6.00 m/s  (19.25ft/s, 11:66 kt)
Probabilities (in %) that EAFB is available
-----------------------------------------------------------------------------------------------
hour |   jan    feb    mar    apr    may    jun    jul    aug    sep    oct    nov    dec
-----------------------------------------------------------------------------------------------
   0 |  72.92  63.31  51.35  38.55  30.58  26.49  28.52  36.61  [illegible]  [illegible]  [illegible]  [illegible]
   1 |  79.02  67.08  48.74  33.05  24.08  18.88  16.17  [illegible]  [illegible]  [illegible]  [illegible]  82.67
   2 |  84.02  75.64  57.98  33.33  [illegible]  16.09  [illegible]  [illegible]  [illegible]  76.02  83.65  85.92
   3 |  86.32  80.81  66.97  46.38  [illegible]  [illegible]  [illegible]  43.52  69.09  81.60  87.53  88.40
   4 |  87.99  83.30  74.04  [illegible]  [illegible]  [illegible]  [illegible]  64.49  81.86  86.03  88.78  89.70
   5 |  89.42  86.02  [illegible]  [illegible]  [illegible]  [illegible]  69.83  75.92  87.04  87.54  89.39  89.21
   6 |  [illegible]  [illegible]  [illegible]  [illegible]  65.41  66.16  76.84  82.77  89.44  87.97  89.03  89.36
   7 |  [illegible]  [illegible]  [illegible]  [illegible]  71.03  71.06  82.05  86.46  90.05  88.87  90.06  89.36
   8 |  [illegible]  [illegible]  78.10  [illegible]  71.68  75.00  85.43  88.32  90.85  89.96  89.86  89.92
   [illegible] |  [illegible]  87.43  82.57  76.95  72.39  74.64  86.82  90.84  92.83  91.19  90.35  90.83
  10 |  90.67  87.38  82.55  78.93  72.71  74.85  88.73  90.82  92.45  92.15  91.70  88.70
  11 |  90.39  88.72  82.20  80.36  77.89  77.95  89.84  93.99  93.96  92.33  92.11  90.24
  12 |  90.85  88.65  84.36  81.07  80.15  80.90  91.38  95.68  94.87  93.50  91.75  90.85
  13 |  90.12  89.58  85.49  83.39  82.52  85.14  94.26  96.06  95.89  95.23  92.71  91.43
  14 |  91.53  91.13  86.86  83.56  79.41  80.55  92.86  96.18  95.90  95.05  93.23  91.37
  15 |  92.69  91.25  86.21  76.38  70.82  71.90  86.73  91.49  93.02  94.25  92.57  91.83
  16 |  91.95  88.46  78.91  70.45  68.01  71.01  84.61  88.63  89.08  90.47  89.78  90.82
  17 |  89.23  83.37  72.67  67.06  68.83  72.08  84.74  87.78  87.27  88.11  86.01  89.52
  18 |  85.61  79.12  68.82  66.16  65.70  72.04  83.99  87.24  85.44  84.73  82.96  86.25
  19 |  82.08  75.10  66.60  63.03  64.41  71.00  81.69  86.64  83.29  82.86  80.35  81.84
  20 |  78.81  71.79  63.56  60.01  61.63  65.84  78.30  81.70  79.19  78.96  76.72  79.09
  21 |  75.80  69.55  61.38  55.40  55.13  59.79  70.18  75.05  76.11  75.68  74.38  76.39
  22 |  74.33  67.08  57.00  49.77  47.64  49.34  58.85  65.99  69.69  74.03  72.14  74.28
  23 |  73.22  63.64  53.47  44.55  39.14  38.42  41.83  53.54  64.28  69.00  69.28  73.37
Annual average %:   75.39
Maximum %:          14.68
Minimum %:          96.18
```

Sample data

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Update Needed

- Shuttle engineers have requested analysis to include various field variables that are not currently implemented in APRA.
- Constellation program has a unique set of analysis requirements, including multi-site network support, oceanic landing zone support, and extended launch windows.
- Both programs have expressed some interest in conditional probabilities for opportunities on days following a given constraint no-go day.
- The analysts who use the tool desire greater run-time flexibility, support for multi-case queuing, and customized tabular and graphical output capabilities.

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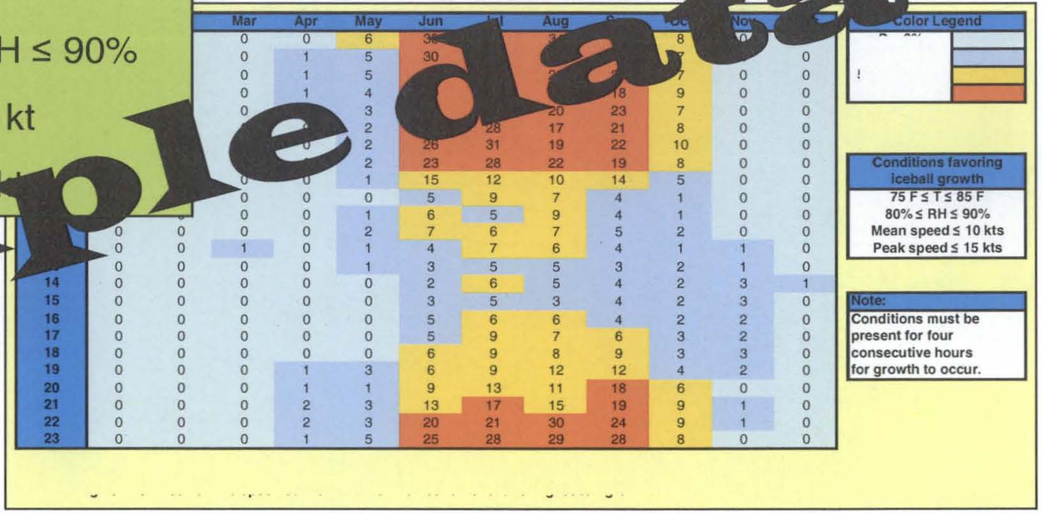
New Capabilities and Applications

Analysis to include humidity and surface pressure

Example application: Shuttle External Tank iceball growth

Conditions Supporting Iceball Growth

- Air temperature: 75 F ≤ T ≤ 85 F
- Relative Humidity: 80% ≤ RH ≤ 90%
- Mean Wind Speed: WS ≤ 10 kt
- Peak Wind Speed: PS ≤ 15 [illegible]



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16	0	0	0	0	0	5	6	6	4	2	2	0
17	0	0	0	0	0	5	9	7	6	3	2	0
18	0	0	0	0	0	6	9	8	9	3	3	0
19	0	0	0	1	3	6	9	12	12	4	2	0
20	0	0	0	1	1	9	13	11	18	6	0	0
21	0	0	0	2	3	13	17	15	19	9	1	0
22	0	0	0	2	3	20	21	30	24	9	1	0
23	0	0	0	1	5	25	28	29	28	8	0	0

Color Legend

Conditions favoring iceball growth

75 F ≤ T ≤ 85 F
80% ≤ RH ≤ 90%
Mean speed ≤ 10 kts
Peak speed ≤ 15 kts

Note:
Conditions must be present for four consecutive hours for growth to occur.

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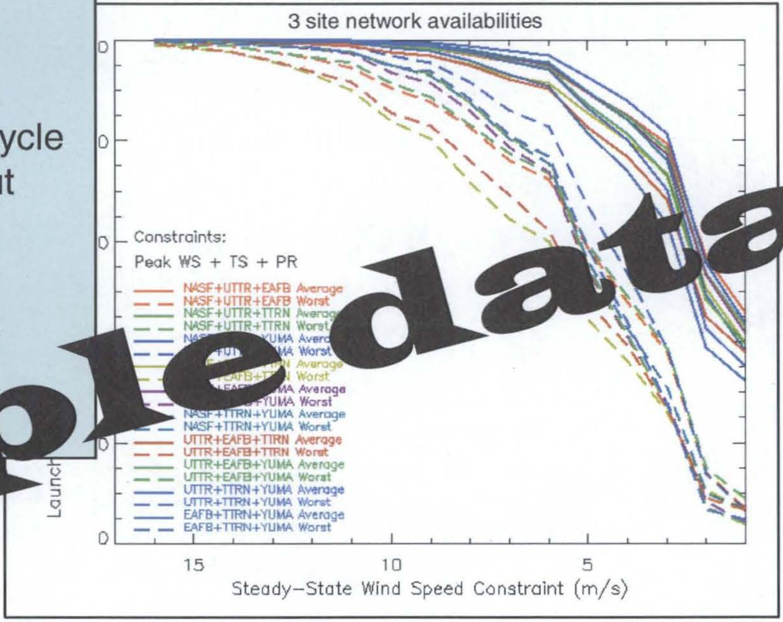
New Capabilities and Applications

Multiple CONUS landing site network analysis

Example application: Constellation “anytime return” requirement

Lunar return is “hot” trajectory (no orbital staging)

- No single site is available for all returns.
- Network configuration greatly affects life-cycle operational cost. Need high availability but with limited number of total sites.
- Program wants high availability. Need to know what set of environmental constraint thresholds give desired availability (how robust must vehicle design be).



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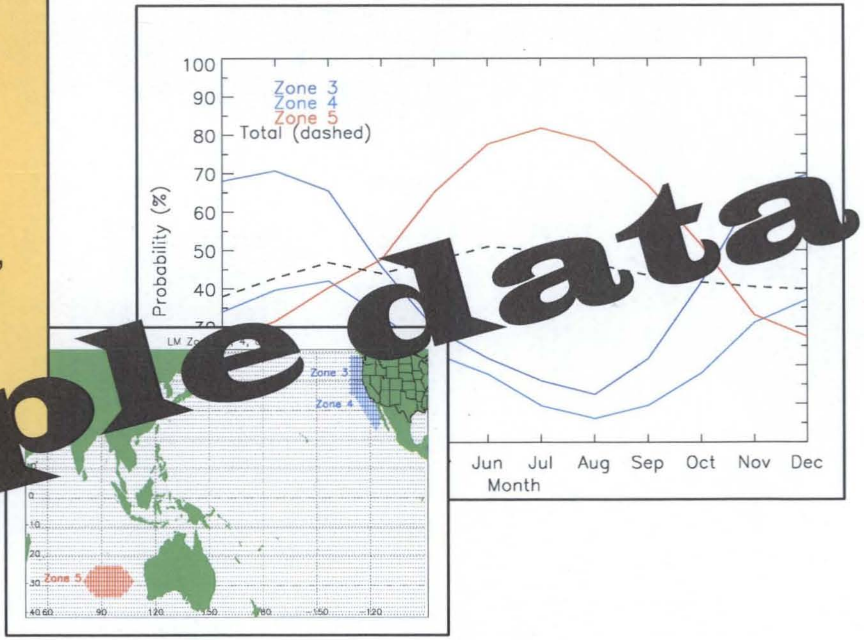
New Capabilities and Applications

Sea state analysis

Example application: Possible oceanic landing zones

Constellation program is considering ocean landing

- Wave height and slope variability are important parameters that must be designed for.
- Data is very sparse. Model data is used, spot-validated with buoy data.
- Sea state analysis also applicable to ascent abort scenarios.



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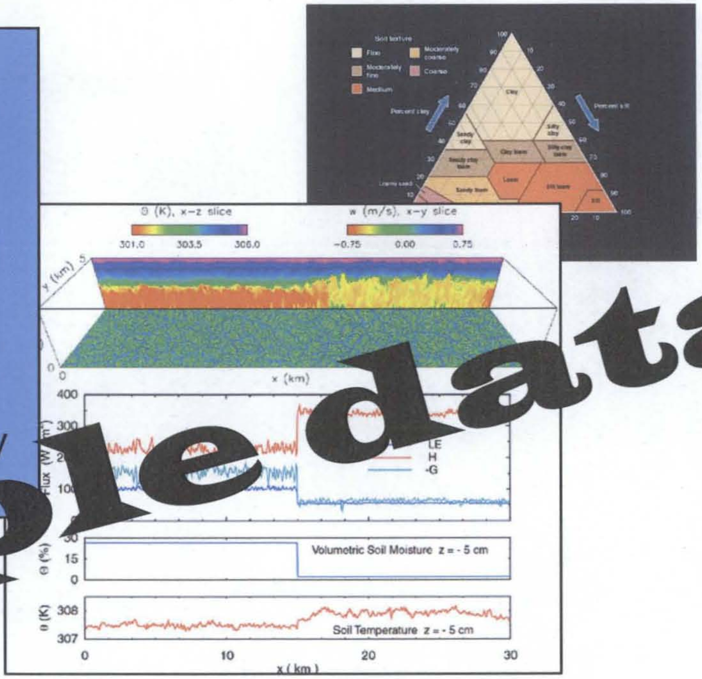
New Capabilities and Applications

Soil properties and surface moisture parameters

Example application: Constellation CONUS landing and recovery

Soil properties have strong influence on landing system design and performance

- Soft soil is easier on vehicle but makes recovery operations more difficult.
- Seasonal ponding on lakebed sites may require more stringent wind speed constraints to avoid capsule tumble and roll-over.
- Limited available data will be added parametrically to analysis.



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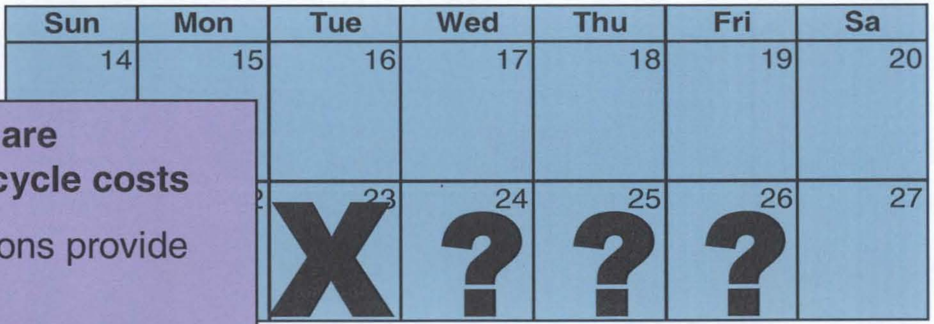
New Capabilities and Applications

Conditional probabilities for launch/landing opportunities following a criteria no-go attempt

Example application: Mission and operations planning



Launch opportunity and vehicle operations cycles are important to overall system operability and life cycle costs

- Longer launch windows for non-space station missions provide flexibility in mission planning.
- "If adverse conditions today preclude a launch, what are the probabilities of similar adverse conditions 24, 48, and 72 hours from now?"
- For nominal lunar return scheduling, it may be beneficial to choose a day with slightly lower availability than another, but with greatly increased conditional probability on subsequent days.

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Implementation Strategy

Scripting language implementation (IDL)

- Reduces IO overhead for successive run executions
- Robust graphics support, customized output formats

GUI driven execution to increase run-time flexibility

- Multi-case queuing (what-if analysis, parameter sensitivity)
- Built-in unit conversion widget
- Conditional analyses, compound data products

Plug-n-play addition of new datasets

- Standardized input format conversion to allow quick inclusion of new parameters, measurement platforms, geographic locations
- Synthesize datasets to produce derivative products

Summary

Major upgrade to be called Probabilities of Atmospheric Conditions and Environmental Risk (PACER).

This is not a formal software development project; work is progressing between other customer priorities as time permits.

Many technical analysis routines have been written. What remains is primarily integrating these into a cohesive framework and implementing them in a flexible graphical user interface.

Targeted completion date is Summer of 2008.

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