Ground Station Selection Investigation for the HyspIRI Satellite Mission

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Abstract – *Hyperspectral Infrared Imager (HyspIRI) is an Earth science mission concept for which a hyperspectral infrared imager is used to map the global land and coastal surface. It is scheduled to launch between 2013 and 2016. The host satellite brings together hyperspectral and multi-spectral instruments to monitor environmental health, volcanoes, wildfires and urbanization. This mission has high data requirements to download three terabytes of data per day. This challenge demands investigation of the system engineering involved with the on-board data storage and mission operation capabilities. This paper investigates the ground station selection methodology and ultimately the decision assessment toward choosing the best ground station combination.*

Keywords: HyspIRI, satellite ground stations, Earth science, hyperspectral, multi-spectral, high data volume.

1 Introduction

The Hyperspectral Infrared Imager (HyspIRI) mission is a high priority mission that would provide global observations of Earth's surface at spatial scales of tens of meters to hundreds of kilometers for a variety of Earth-system studies [1]. HyspIRI consists of two instruments: a hyperspectral imaging spectrometer and a multi-spectral scanner. These are high data volume instruments developed at the Jet Propulsion Laboratory (JPL). Together these instruments produce almost three terabytes of data per day and are expected to produce a petabyte of data over its three-year lifetime. During development of the HyspIRI mission concept, it became evident that the correct ground station configuration needed to be evaluated. This configuration would need to handle large data volumes, be reliable, and be accessible in order to utilize the data collected. This paper investigates the creation of decision making tools for choosing a suitable ground station configuration for the HyspIRI mission.

1.1 Hyperspectral Instrument

The hyperspectral instrument, or visible to short wave infrared (VSWIR) spectrometer, is utilized to research a large bandwidth from 380nm to 2510nm with 14 bands of spectral data [2]. Utilizing this instrument on HyspIRI would make potential data base prevention and program implementation options available to decision makers. It operates at a 60m/pixel resolution with a 288.5 Mbps (mega-bits per second) data rate during the day when the sun is at an inclination angle of 20°. This instrument's measurements dominate the stored on-board data. It will be used for global plant mapping and detecting vegetative health. It has a push-broom rectangular view field with a 145m by 45m footprint. This focuses on the land and coastal regions except for Antarctica. The deep ocean data is not of primary importance to the mission scientists; therefore the data is compressed during the time the instruments pass over such regions [3].

1.2 Multi-spectral Instrument

The multi-spectral instrument or thermal infrared (TIR) multi-spectral scanner is used to acquire thermal imagery to monitor volcanic activity, urbanization, ecological health, and wild fires. This is a whiskbroom scanner that has a large 600m by 45m rectangular field of view, which calls for a 5-day revisit time (time between satellite-based observations of the same point on the Earth). It operates day and night at a data rate of 74Mbps. The TIR measurements do not dominate the data collected by HyspIRI. It requires 41% of the total on-board data storage. It focuses on the land and coastal regions as well, but does not focus on Greenland and Antarctica. The deep ocean is not as important to the TIR scientists, but they do require a lower resolution of ~1000m/pixel and a higher compression of 200Mbps [3]. The lower resolution relieves some of the data storage required over these regions.

2 Assumptions

Reconciling the two revisit times associated with the instruments required a separate tool to determine an optimal attitude used as an input to the sun-synchronous orbit expected for HyspIRI. The mission requirements therefore set forth an orbit, swath width, and expected data rates as prescribed in [2]. Fig. 1 shows the expected data distribution for various landforms and overall data contributions from each instrument.

The revisit time attitudes and associated orbits were combined to determine the data uplink rates that the satellite would accept on-board during operation while approaching a ground station. The ground station downlink rates were researched to be between 100Mbps and 300Mbps. The mission assumed that ground stations would be upgraded to X-band, which called for rates of 740Mbps and 800Mbps as currently utilized by GeoSAT. These simulations are done with 19-day cycle data to accommodate the complete cycle of the hyperspectral imager. The simulation assumes a completely cloudless sky. A cloudless sky means that data will be acquired at the highest data rate without dumping any data during the entire life of the system. This is the worst case scenario for the largest amount of data received, but also an unrealistic assumption with respect to the health of the Earth.

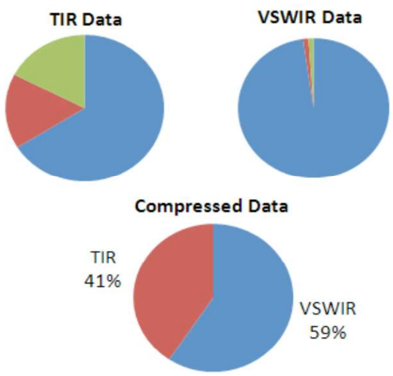

Figure 1. HyspIRI data distribution for land (blue), clouds (red), and ocean (green).

3 Objectives

There are specific Mission Operations objectives to address the on-board data storage and mission design aspects of the HyspIRI mission. The first considers distinguishing the best swath width and ground stations to satisfy the decadal survey requirements. This is done by creating individualized ground station objective functions, which diagnose the capabilities associated with each ground station. The next objective is to see how combining these ground stations would impact the on-board storage. In order to achieve this, an orbital analysis program was utilized to model the uplink and downlink flow of data from ground to satellite to ground station. This ultimately monitored the total on-board data storage. Examining this information gave insight as to which combinations were feasible. Once feasible solutions were identified, another objective function along with constraints was applied to determine which feasible solution was the best.

4 Tools

In order to answer these Mission Operation Objectives, tools were identified to model the mission operation design. Simulation processes were created to investigate the robustness of the system. The first tool used was the Aerospace Corporation's Satellite Orbit Analysis Program (SOAP). This is a satellite orbit modeling tool that allows the user to model the orbit and sensor path swath associated with each instrument (see Fig. 2).

This effectively records swath exposure time to the various ground stations and data of interest for each instrument. By utilizing SOAP, the downlink and uplink time exposures are recorded for each instrument and potential ground station. This total time can be translated into data volume given the data rates for each instrument.

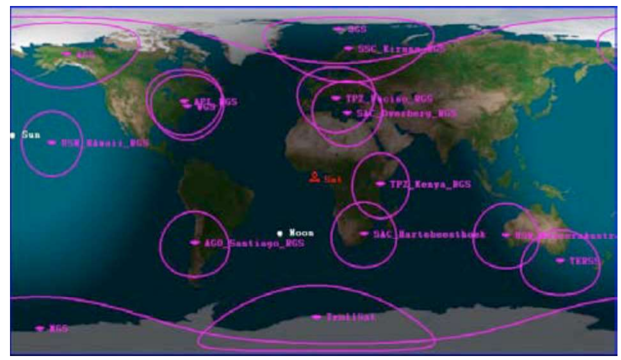

Figure 2. SOAP Cartesian viewpoint of the Earth and potential ground stations.

Additional tools consisted of Perl scripts. Perl is a programming language that allows one to script the execution of multiple disparate software applications. These scripts first found the optimal altitude and swath pattern. Both instruments have extremely different revisit times and swath patterns. In order to combine these two instruments into one mission it was necessary to investigate the swath pattern, area, and potential revisit time. This correlates to a certain attitude that was utilized in the SOAP model to create the HyspIRI model. The next Perl script was a post-processing tool that showed the effects on the on-board data storage using the SOAP downlink access times to ground stations, events, and data uplink times.

4.1 On-Board Data Storage

Utilizing the results from the swath pattern, attitude, and inclination angles the SOAP scenario was created to include the satellite mission operations, instrument data collection maps, and possible ground station downlinks. The SOAP scenario provided the downlink times over the entire 19-day period for each instrument [2]. The Perl scripts provided the means to translate the time available to data stored [3].

4.1.1 Inputs

The Perl script takes the data upload rate for each instrument and Ground Station Downlink and integrates the perspective actions into one time history of the on-board data storage. A sample input scenario is shown in Fig. 3. The positive values represent data taken on-board the satellite while negative values represent data being downlinked from the satellite.

Datatakes.csv	317
Datatakes1.csv	74
DownlinksAtAGS.csv	0
DownlinksAtMGS.csv	-800
DownlinksAtSGS.csv	-800
DownlinksAtSSC_Kiruna_RGS.csv	0
DownlinksAtTERSS.csv	-800
DownlinksAtTrollSat.csv	0

Figure 3. Sample input scenario.

4.1.2 Outputs

The Perl script outputs are data files that represent the on-board data storage in megabytes vs. time in seconds at 30-second intervals. These data were graphed as shown in Fig. 4 and used to determine the best ground station configuration.

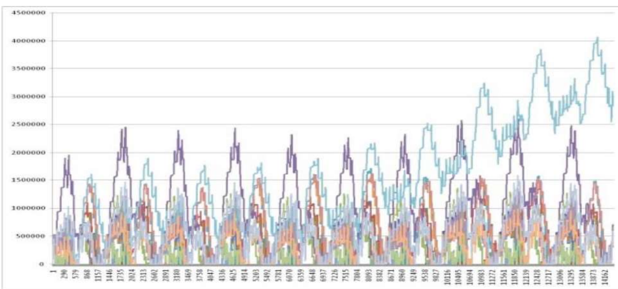

Figure 4. Sample output graph of data storage vs. time generated by Perl script.

4.1.3 Ground Stations

An important characteristic of any ground station is its latitude placement on the Earth/s surface. The latitude corresponds to the specific time length and frequency that a satellite may communicate with a given ground station. The polar stations at high latitudes operate at the highest frequency while ground stations at the equator operate at the least frequency. Therefore, placing ground stations at high polar latitudes is advantageous to the downlink time available to this particular orbit.

Mission operations for HyspIRI assumed polar ground stations. A list of 20 ground stations was chosen to study the communication downlink phenomena. The mission anticipated upgrading the ground stations to accommodate the high data volumes. The team decided to investigate upgrading the ground stations to either a 740Mbps or 800Mbps data rate capability which are currently in use. The study included all 20 stations to investigate which combinations could handle the data flow. The number of ground stations was later reduced to a set of feasible options to be explored [3].

4.1.4 Decision Making Tools

The tools provided the raw data to show which ground station configuration affected the data. These data were mapped and yielded extremely large data sets that corresponded to 19 days worth of on-board data. In order to compare one data set to another, a decision making tool needed to be created to take into account statistical information about the on-board data storage [4]. The characteristics of each data run were determined by the maximum peak in the data, the slope, and average value determined by adding a linear trend line to the data. In addition to these statistical characteristics, the configurations were also subjected to the cost associated with upgrading the configuration, the assumed reliability, and finally the political control of each ground station. These criteria provided a basis for characteristics that were used in an objective function, for an individual ground station, to determine the best configuration of the possible combinations as follows:

$$GS_{ObjFunc} = \alpha\left(\frac{L_T - L_A}{L_T}\right) + \beta\left(\frac{A_T - A_A}{A_T}\right) + \gamma\left(\frac{R_T - R_A}{R_T}\right) + \delta\left(\frac{D_T - D_A}{D_T}\right) + \varepsilon\left(\frac{P_T - P_A}{P_T}\right) \quad (1)$$

where the parameters in Eq. 1 are defined below and the multiplicative coefficients satisfy Eq. 2.

$$\alpha + \beta + \gamma + \delta + \varepsilon = 1 \quad (2)$$

- L: Latitude Access time according to ground station latitude position
- A: Accessibility, or the number of times that data can be gathered from ground stations
- R: Reliability, or the amount of time that ground stations do not function
- D: Downlink Capability, or ground station data rate
- P: Political Control of the ground station by a country (1.0, 0.5 or 0.0 corresponding to total, collaborative, and non-collaborative country control, respectively)

In Eq. 1, the T subscript represents the target value and the A subscript represents the actual value. The target values for individual ground stations are listed in Table 1.

Table 1. Individual Ground Station Target Values.

Attribute	Value
Latitude Access Time	10 min
Accessibility	30 days per month
Reliability	100%
Downlink Rate	800 Mbps
Political Control	1

After assessing the individual ground station information, the score (GS) is utilized along with the maximum peak in the data (M), the slope (S), and average value (Avg) to determine the aggregate combination score given in Eq. 3. These objective function target values are listed in Table 2.

$$ObjFunc = \alpha\left(\frac{M_T - M_A}{M_T}\right) + \beta\left(\frac{S_T - S_A}{S_T}\right) + \gamma\left(\frac{Avg_T - Avg_A}{Avg_T}\right) + \delta\left(\frac{GS_T - GS_A}{GS_T}\right) \quad (3)$$

$$\alpha + \beta + \gamma + \delta = 1 \quad (4)$$

Table 2. Target Values of Objective Function Attributes.

Attribute	Value
Maximum Peak	1.6Tb
Average Value On-Board	0.2Tb
Slope	0
Individual GS Score	100%

Five scenarios were created (see Table 3) from which to choose the best ground station configuration emphasizing maximum peak storage, average on-board storage, data slope, geography, reliability, and cost. The next section presents results of an analysis of these scenarios.

Table 3. Ground Station Configuration Scenarios.

Attribute	Scenario				
	1	2	3	4	5
Max Peak	16.6%	50%	10%	10%	10%
Avg. Val	16.6%	10%	50%	10%	10%
Slope	16.6%	10%	10%	50%	10%
Geography	16.6%	2.5%	2.5%	2.5%	10%
Reliability	16.6%	2.5%	2.5%	2.5%	10%
Cost	16.6%	25%	25%	25%	50%

5 Results

The individual ground station score and graphical composite score were used to model the on-board data storage. Scores for a set of ground stations are listed in Table 4. Fig. 5 shows plots of on-board data storage versus time for the case of utilizing one ground station, revealing that no single ground station can handle the data downlink.

Therefore, the top six ground stations were used to search for the best combination for the next sets of results. The top individual scored ground stations were consistent with the top six graphical ground stations in Table 4. The top six ground stations are listed in Table 5 where the order is given by the graph rankings and the second column lists them based on their individual ground station score.

In the subsections below, combinations of two and three ground stations listed in Table 5 are analyzed. Each combination is denoted by a numerical code "ij" for combinations of two ground stations, and "ijk" for combinations of three, where i, j, and k are reference numbers from Table 5. For example, the combination of ground stations Svalbard and TrollSat is designated as code 36.

Table 4. Individual Score for all Ground Stations.

Ground Station	Individual Score
AGO_Santiago RG	0.4275
AGP_Santiago_RGS	0.4275
AGS	0.750833
APL_RGS	0.4925
MGS	0.52
SAC__Hartebeesth	0.4675
SAC_Hartebeesthoek	0.4675
SAC_Overberg_RG	0.44
SAC_Overberg_RGS	0.44
SGS	0.736333
SSC_Kiruna_RGS	0.610833
TERSS	0.636167
TPZ_Fucino/_RGS	0.4575
TPZ_Kenya_RGS	0.5025
TrollSat	0.5265
USN_Hawaii_RGS	0.4775
USW_WesternAust	0.4525
USW_WesternAustralia_RGS	0.44
WGS	0.39

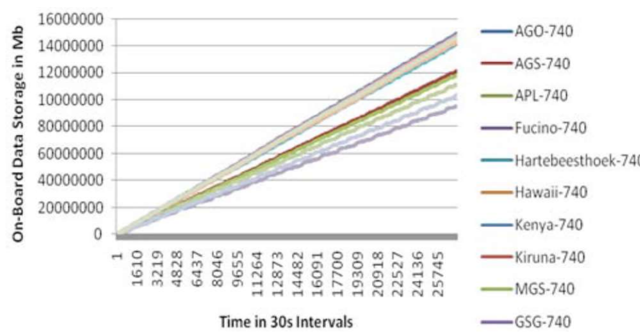

Figure 5. One ground station upgrade for the top six ground stations.

Table 5. Top Six Ground Stations.

Reference Number	Ground Stations
1	Fairbanks, Alaska
2	McMurdo (Antarctica)
3	Svalbard
4	Kiruna, Sweden
5	Tasmania
6	TrollSat (Antarctica)

5.1 Two Ground Stations

A full factorial of upgraded ground stations for two combinations was performed. The results are shown in Fig. 6. For example, Trial 36 (Svalbard and TrollSat) is the lowest data series displayed on both two ground station combinations shown in Fig. 6. It displays the correct wavy nature showing that this combination is having a significant impact on downlinking the data. Higher data streams show an unstable waveform (e.g., Trial 34, Svalbard and Sweden, the highest data stream on top), without the steadiness displayed for Trial 36. This is the desired waveform since it guarantees a lower overall average for the data expected on-board.

The general waveforms of both the 740Mbps and 800Mbps are the same. The only difference is the degree to which each ground station combination can downlink the data. The order of the ground station combinations remains the same.

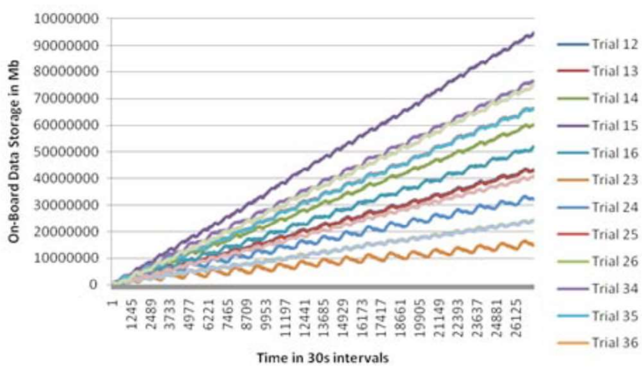

Figure 6. Two ground stations upgraded to 800 Mbps.

Two ground stations cannot handle the current data rates at either upgraded downlink rate. Either the configuration needs another ground station or the data rate must be lowered in order to meet the HyspIRI mission requirements. Comparing this to simply adding the individual ground station scores together, we see that the sum of individual scores predicts that combinations 13, 14 and 34 are the best. This is contrary to the graphical outputs as seen in Fig. 6.

5.2 Three Ground Stations

Investigating three ground station combinations yielded results for handling the on-board data storage as shown in Fig. 7. The two-ground-station analysis yielded incomplete results, which meant that they contradicted the graphical analysis. Looking at the combined score for three ground stations predicts that 135, 136, and 123 will be the best combinations. Results below (Sect. 5.3) show that the best solutions actually include 136 and 123, but not 135 – the best predicted solution.

Again, the individual ground station score cannot be used autonomously to choose the best ground station scenario. Closer views of these solutions are shown in Fig. 8 and Fig. 9.

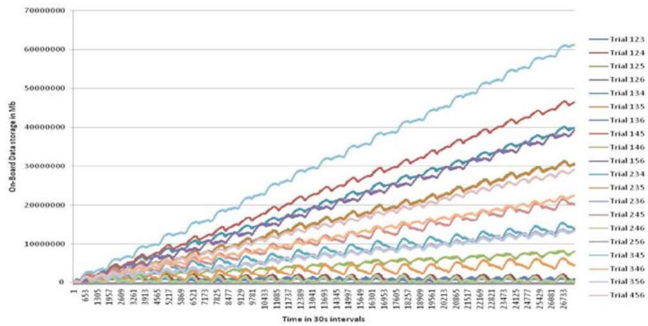

Figure 7. Three ground stations upgraded to 740 Mbps.

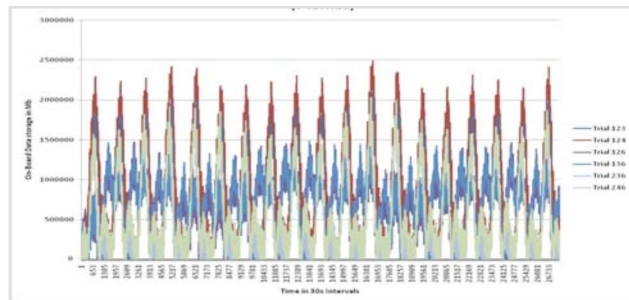

Figure 8. Three ground stations upgraded to 740Mbps.

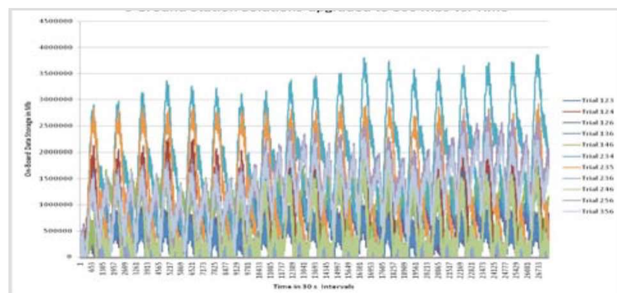

Figure 9. Three ground stations upgraded to 800Mbps.

Of the 40 possibilities there are 16 feasible solutions. While these are feasible solutions, they do not have the physical on-board data constraint imposed upon them. As stated earlier there is a 1.6Tb on-board data constraint imposed on the ground station configuration. This is not included with the predicted individual scored ground stations. However, it is included in the aggregate ground station score.

Imposing the on-board data storage constraint reduces these feasible solutions from sixteen to only four possible solutions. This is shown in Fig. 10 and Fig. 11. Note that all four solutions are really only two solutions at both downlink rates. This suggests that the lower data rate is feasible, and while the higher downlink rate gives a better margin for on-board data storage, utilizing a lower data rate may be a cost savings. The individual ground station score did predict that combination 136 was among the top three scores, but it only scored second in the lineup. The first solution of 135 was not even included among the feasible solutions.

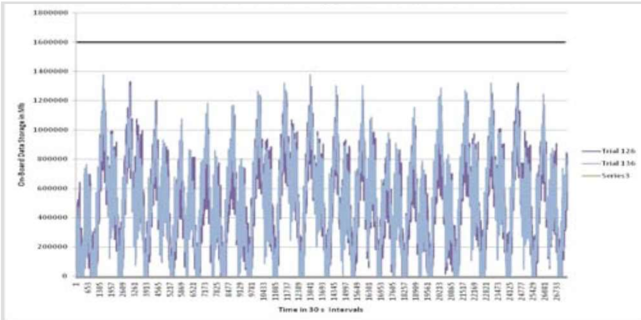

Figure 10. Three ground stations upgraded to 800Mbps; solutions with 1.6Tb constraint.

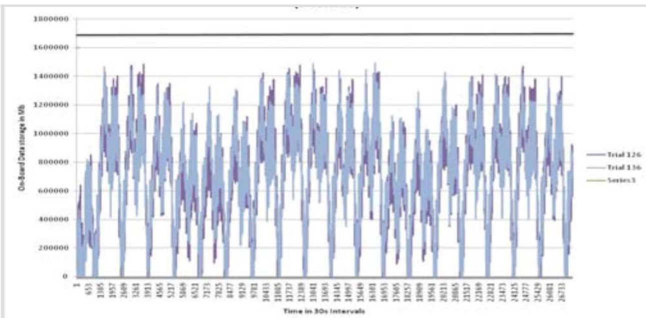

Figure 11. Three ground stations upgraded to 740Mbps; solutions with on-board data constraint of 1.6Tb.

5.3 Ground Station Configuration Summary

Figure 12 summarizes the results of the feasible and constrained ground station configuration solutions. There is a mere 5% of feasible solutions at the current on-board data constraint. However, 40% of the possible solutions are feasible solutions. This information should be taken into consideration when considering increasing the on-board data constraint or when negotiating possible ground stations.

The individual scores of the ground stations that produced feasible results at both 800Mbps and 740Mbps are consistent with the theme of 123 and 136 as the best possible combinations with both their individualized normal scores linearly combined and normalized as listed in Table 6. It also shows that the second feasible constrained solution of 126 had a lowered normalized individual score.

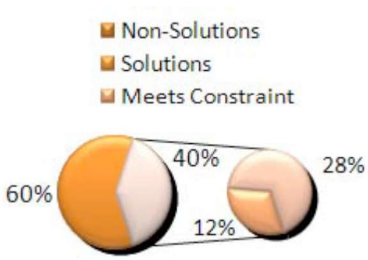

Figure 12. Ground station configuration results.

Table 6. Feasible Ground Station Combinations with Individual and Normalized Individual Scores.

Ground Station Code Combination	Individual GS Score	Normalized Ind. GS Score
123	2.007	1.173
124	1.882	1.099
126	1.797	1.054
136	2.014	1.488
146	1.888	1.101
234	1.867	1.089
235	1.893	1.103
236	1.263	0.905
246	1.657	0.960
256	1.683	0.975
356	1.899	1.106

5.4 Ground Station Scenario Analysis

Previously each data series was compared to the others to get a sense for the comparable characteristics of each configuration. Table 3 suggested configuration scenarios to which the objective function was applied. Table 7 shows the results of the scenario analyses. The objective function not only gave the best scenario for each combination, but also showed that the 235 combination (McMurdo, Svalbard, Tasmania) at 800Mbps was the worst combination.

Table 7. Objective Function Results.

Scenario	Best Combination	Emphasis
1	136 @800Mbps	All Equal
2	126@800Mbps	Maximum Peak
3	236@800Mbps	Average Value
4	136@800Mbps	Slope
5	123@800Mbps	Cost

Examining Table 7, one can see that in every combination except for Scenario 5, TrollSat (6) was included as a best solution. Everything else was a combination of ground stations 1, 2 and 3. Fairbanks (1) was the next most common ground station chosen with McMurdo (2) and Svalbard (3) tied for third place. Sweden and Tasmania were never chosen for the best scenario case. This does not mean that they were not feasible solutions, but only that they were never chosen as the best solution for the specific criteria considered. For the sake of complying with current constraints, Scenario 2 was chosen as the ground station configuration since it was the best scenario that also met the 1.6Tb data constraint.

6 Conclusions

The procedure presented herein depicts an approach to assessing a high data volume downlink capability requirement in relation to selection of ground stations for the HyspIRI mission. The solution calls for the mission requirements to be used as inputs to an objective function to determine the desirability of each ground station. Using this information, ground station selection can be reduced to the most prominent possibilities. This information can then be designated to find the correct combination of ground station capabilities and ultimately used as input to another objective function to determine the overall desirability of the configuration. This information can then be used to predict the various effects of different scenarios on ground station selection. The individual ground station scores were indicative of the future aggregate ground station selections. This scenario is limited to the underlying high data volume and low Earth orbit assumptions. However, it is general enough that is can be attributed to various cases when selecting satellite ground station connections or even during ground station planning.

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