Reducing Link Budget Requirements with Model-Based Transmission Reduction Techniques

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ABSTRACT

As a mission design envisions travel further from Earth, transmission power and onboard or ground-based antenna sizes must be increased to maintain a given transmission throughput. However, onboard capabilities are constrained by volume and mass limitations, thus constraining a mission's science-value. Model-based transmission reduction (MBTR), is a 'game changing' technology that allows greater science to be performed (and the results transmitted to Earth). Instead of conventional link requirement reduction approaches, which make marginal reductions by compression techniques, this approach intelligently reduces data transmission requirements by transmitting only the differences between a shared (between the spacecraft and ground analysis site) model and the data required to support these change assertions.

This paper discusses model development, a model definition language, and a communications framework for MBTR transmission. It discusses the onboard autonomy requirements for a MBTR mission and reviews how the link budget requirements, under this model, become a function of the accuracy of the initial model and the magnitude of validation data required by mission scientists. The benefits of MBTR for small satellite missions within the solar system and its requirement for interstellar missions are discussed.

1. INTROCUTION

Any small satellite development program is forced to consider numerous tradeoffs. In the realm of communications, power, space and mass can be traded for additional gain and faster data-rate communications. Alternately, larger ground stations can be used to the same end. However, as mission plans envision a small spacecraft moving further from Earth, even the aforementioned are hard pressed to keep pace with the loss due to distance. Thus, with a conventional communications approach, the science-value of the mission is constrained by the ability to transmit images and other data back to Earth for analysis.

The proposed approach, model-based transmission reduction (MBTR), represents a transmission approach paradigm shift that allows greater science to be performed (and the results transmitted to Earth). Instead of conventional link requirement reduction approaches, which make marginal reductions by compression techniques, this approach intelligently reduces data transmission requirements by transmitting only the differences between a shared (between the spacecraft and ground analysis site) model and the data required to support these change assertions.

2. BACKGROUND

Bozzi, et. al. [1] proffer that data compression is "not considered standard for critical deep-space missions". However, those operating smaller spacecraft, such as those of the SmallSat and CubeSat form factor, will likely require some form of compression in order to transmit the data that is required to achieve their scientific and other objectives.

Previous missions, such as the Helioseismic Magnetic Imager (HMI) Instrument aboard the Solar Dynamics Observatory have utilized compression as part of their mission design [2]. The HMI crops images and performs lossless compression using hardware image processing boards. The design of the High Time Resolution Spectrometer (HTRS) instrument on the International X-ray Observatory, incorporates compression for lists of time stamp, silicon drift detector and energy data [3]. Simulations created during the planning process indicated that the compression was achievable up to the level of 50%, for this type of data when CPU-intensive compression software was utilized.

The Galileo mission, in response to a failure of the high-gain antenna, implemented an image compression approach that was similar to the JPEG standard [4]. This allowed a ten-fold improvement in the level of images and other data versus the projections of what was believed capable utilizing only the low-gain antenna, prior to the failure [5].

Faria, et. al. [6] compared a variety of image compression techniques in the context of a satellite imagery application. Their work indicates that compression ratios of up to 353.5 may be possible; however, the quality of the imagery may not be suitable for various needs.

3. THE MBTR PARADIGM

MBTR is not a data compression technology, despite the fact that it results, effectively, in the transmission of more data over less bandwidth. It is, instead, an alternate paradigm for dealing with data. MBTR consists for four levels, ranging from model-based data transmission to model-based finding transmission. Each level represents a higher-value data product and requires more autonomy than the levels below it

Model-based data transmission (MBDT) utilizes a model in the transmission of the data. With this approach, data is compared to a shared model (or possibly a co-transmitted model) and discrepancies between the model and the actual data are identified and transmitted. MBDT can transmit all discrepant areas or can be restricted to transmit only areas of discrepancy over a certain threshold value. The fundamental notion of MBDT is that data can be prioritized by importance (represented by the level of difference from the model), and selected for transmission based on this priority.

Model-based data analysis (MBDA) goes beyond just identifying the most important areas of data to transmit. It involves actually performing context-aware analysis to determine what data sets or elements of data sets are most important and should be prioritized for transmission. Thus, while MBDT can be applied without an understanding of the meaning of the data, MBDA requires this context to be understood.

Model-based result transmission (MBRT) extends the analysis performed under MBDA to actually produce a conclusion. Under MBRT, thus, data can be prioritized by the value of the thesis that it supports or refutes and the level of support or refutation that it provides, as opposed to just its relative utility.

Model-based findings transmission (MBFT) is the highest level of MBTR. Under MBFT, a model of a phenomena of interest is evaluated autonomously onboard the spacecraft. Discrepancies between the model and the observational data are noted and the model is updated based on this. Data to allow validation of the autonomous decision-making can be returned along with the model updates in order to facilitate acceptance by the scientific community.

4. MODEL-BASED DATA TRANSMISSION FOR IMAGE DATA

All approaches to MBDT utilize a model and convey prioritized differences between the pre-existing model and the detected data. For the MBDT of image data of an asteroid presented here, this model is a low-resolution image which, presumptively, could have been taken from the surface of Earth, or an orbital telescope. For the purposes of this experiment, the a lower-resolution version of the same image that would be transmitted was used; in actuality, the a corresponding image from the model database would need to be located and features matched to align the model and observations. An existing feature-based image alignment technique [e.g., 7, 8] could be utilized for this purpose.

The image is then processed by the algorithm looking for the areas that are the most divergent from the model. This has the effect of increasing the resolution of features that may not be visible in the lower-resolution imagery, while paying less attention to minor fluctuations in shading, etc. across an area. Image areas can be prioritized for transmission based on this divergence value; or a threshold difference level can be established and all areas with values above that level will be transmitted.

In the experimentation discussed herein, the area was defined to be a single pixel; however, future research could prioritize regions based on a combination of the average level of difference and size. Thus a larger feature that had less per-pixel difference could have a similar or greater level of prioritization than a single pixel that was particularly divergent. This would be an important consideration if the imaging system was prone to the introduction of single-pixel noise during acquisition, transfer or pre-processing storage.

5. MODEL DEVELOPMENT FOR MBDT

Two model development approaches are contemplated for MBDT. Under the first, a pre-shared model is created prior to craft launch. This could be captured by a ground-based instrument or could have resulted from previous fly-by or orbital observations. Under the second approach, a model is created as part of the observations. This approach might be utilized if no data exists on a target, the data is found to be so inaccurate as to render the initial model unusable or there are gaps in the data such that the transmission of a model before transmitting data would speed the transmission process.

In any event, for image data, the model is generally a low-resolution image of the target. The comparison of various levels of model versus high-resolution imagery resolutions is presented in section 9. Other data types would have similar models; for example, a composition map model could be transmitted with a significantly lower level of granularity than the actual data.

6. MBDT MODEL DEFINITION LANGUAGE

The model definition language for the low level (MBDT) data is the most data centric. The TIFF format has been principally utilized for the purposes of the experimentation performed herein. The bitmap and JPEG formats were also evaluated. TIFF and bitmap performed suitably in all cases. The JPEG format, particularly with high compression/low quality levels, introduced artifacts or other anomalies that sometimes required additional change messages to correct for. The level of tradeoff between the heightened compression for model transmission (presuming that use of a pre-shared model is not feasible) will be a subject of future research.

7. MODEL CHANGES & VALIDATION

For imagery data, model changes consist of three parts, a header, a section header, and section data. Data is segmented into sections so that a local addressing scheme can be utilized to preclude the need to transmit several bytes for identifying each pixel-change in a global context.

A. Header

The header contains a craft identification field, transmission identification field, transmission sequence number, date / time stamp field, and validation field. All fields are variable length and delimited by the ASCII 13 carriage return character. It is expected that the MBDT transmissions will be further encapsulated as part of lower-level transmission protocols.

The craft identification field is a locally unique value that identifies the source craft. This field is included based on a presumption that some crafts may relay data for others. At higher MBTR levels, they may also process this data and transmit only results and associated validation data, based on the data collected by the lower level craft. The craft identification field identifies the initial source of the data.

The transmission identification field serves two purposes. First, it uniquely identifies the transmission to allow proper reconstruction of a transmission that may be spread across multiple high level messages. The use of multiple high-level messages is anticipated in cases where high priority data may be transmitted at one time, and lower-priority could later be transmitted on a space-available basis.

The transmission identification field will also identify the type of the data being sent and the target that it applies to. The specifics of the format of this field are left to the individual mission designer to determine.

The transmission sequence number is used to identify subsequent messages relating to a given transmission. For the individual-pixel change messages used in this experiment, this is not critical. However, if region-level changes are applied and then pixel level changes applied over top of the regional changes, the order of change application becomes critical and, thus, knowing the message order for application is required.

The validation field can be used to store a checksum or hash value that can be utilized to validate that the data has not been erroneously or intentionally modified during transmission. The specific check digit or hash algorithm utilized in this field is left to the individual mission designer to select. If the lower level communications protocol provides both data and channel integrity, then this field can be left blank.

B. Section Header

The section header serves to identify the location of the section within the larger image. A section is defined by a X, Y coordinate pair. Each section is 256x256 pixels, such that local addresses can be represented by a single byte (minimizing data size). The section header contains two fields: section location and length. The section location field consists of two five-byte values. It is followed by a two-byte length field.

C. Section Data

Section data immediately follows the section header. Section data for image files consists of the local coordinates for each change and the change to be made. Two possible approaches for the coordinates are possible. In cases where it is expected that few changes will be required (less than one per line, on average), the coordinate set will include a one-byte x and one-byte y coordinate. In cases where it is expected that one or more changes will be required on most lies, only the x coordinate is utilized and lines are delimited by a trailing set of all zeros (x-coordinate=0, all zeros for the change value). The coordinate system starts from a minimum 1, 1 point so the zero value is not ambiguous.

8. ONBOARD CAPABILITY REQUIREMENTS

The onboard capability requirements for MBTR are significant. They increase with each level (from MBDT to MBFT) as each level must perform the work of the lower levels plus progressively more complex and processor-intensive work. MBDT, thus, requires the lowest level of throughput. The work performed (described in section 9) allows the inference (based on the extrapolation from the time required for performance on a standard desktop computer) that MBDT can be accomplished within a reasonable amount of time (several minutes or more per image) on a processor typical of a flight computer for a small satellite. Current work focuses on getting MBDT operating on a GumStix computer-on-module, which would be a technology suitable for use in a small satellite [9].

9. EXAMPLE: MBDT ON VESTA IMAGERY

Software that implements the MBDT methodology described in the proceedings sections was created. It was tested utilizing both simulated and pre-existing spacecraft-sourced data.

A. Experimental Design

For the purposes of this experiment, imagery taken by the DAWN Framing Camera (DFC) of asteroid Vesta was utilized [e.g., 10]. This imagery was reduced in resolution (downscaled) and increased in resolution (upscaled) resulting in an image that was the same size as the native DFC image, but with a significantly lower resolution.

Several different model image sizes (which are based on the size of the low-resolution image that was upscaled to produce the same-file-size model) were tested. For each model size, several threshold (the minimum difference required to include a change in the data stream) were tested. Table 1 presents the resulting file sizes for the changes for each model size/threshold combination. Note that a two-byte identifier was used for the local address and brightness correction, which is different from the format described in section 7C. However, as both can be replaced by a one-byte field, the relative differences (as a percentage/multiple) are the same as if one-byte fields had been used. Table 2 presents this data as percentages for comparative purposes. Tables 3 and 4 show the transmission required for both the model and model corrections as bytes and as a percentage of the file size of the image, respectively. Note that on all tables the model size percentage is a percentage of the height and width, not the area. Thus, the 50% model size actually has a height and width at 50% of the original and is 25% of the area and (roughly) file size.

B. Performance Evaluation Metrics

There are two key metrics that are relevant to the evaluation of the performance of MBDT. The first is the qualitative metric presented in tables 1-4: transmission size. The second is the qualitative quality of the imagery. Image processing research has identified several ways to evaluate the quality of images that have been enhanced or otherwise processed [11]. However, evaluating performance relative to the requirement to convey the maximum level of scientific data is not well aligned with these standard methods. The average pixel difference is not a suitable metric as it fails to consider the relative importance of some pixels (e.g., those that are enhanced) versus others. Measures of visual appeal are similarly irrelevant. Visual evaluation was utilized to select examples of well performing model-size/threshold combinations. However, the specific application that is being contemplated may place greater emphasis on various aspects of quality and performance should be evaluated in this mission-specific context.

10. EVALUATION OF MBDT PERFORMANCE

The performance of the MBDT approach was shown to be adequate at several combinations of threshold value and initial model size. Given that the initial model could be compressed using an image compression technology (such as those described in section 2) the comparison of the model size and change file sizes is of minimal relevance.

The work that has been performed demonstrates the

Table 1: Bytes required for model correction transmission as a function of threshold and model size.

Threshold	Model Size: 5%	10%	15%	20%	25%	50%
5%	157784	137706	122722	123340	122053	65478
7%	122706	104188	90324	91932	90206	35171
10%	88833	66938	53665	56443	56127	13633
15%	46573	33082	24984	27676	27062	3372
20%	25897	15367	11933	13383	13813	962
30%	6743	3227	2551	3418	3754	269
50%	417	341	333	365	361	257

Table 2: Data transfer required for model correction as a percentage of image size

Threshold \ Model Size	5%	10%	15%	20%	25%	50%
5%	119.2%	104.0%	92.7%	93.2%	92.2%	49.5%
7%	92.7%	78.7%	68.2%	69.5%	68.2%	26.6%
10%	67.1%	50.6%	40.5%	42.6%	42.4%	10.3%
15%	35.2%	25.0%	18.9%	20.9%	20.4%	2.5%
20%	19.6%	11.6%	9.0%	10.1%	10.4%	0.7%
30%	5.1%	2.4%	1.9%	2.6%	2.8%	0.2%
50%	0.3%	0.3%	0.3%	0.3%	0.3%	0.2%

Table 3: Bytes required for model and model correction transmission as a function of threshold and model size.

Threshold \ Model Size	5%	10%	15%	20%	25%	50%
5%	158112	139017	125672	128583	130245	98246
7%	123034	105499	93274	97175	98398	67939
10%	89161	68249	56615	61686	64319	46401
15%	46901	34393	27934	32919	35254	36140
20%	26225	16678	14883	18626	22005	33730
30%	7071	4538	5501	8661	11946	33037
50%	745	1652	3283	5608	8553	33025

Table 4: Data transfer required for model and model correction as a percentage of image size.

Threshold \ Model Size	5%	10%	15%	20%	25%	50%
5%	119.5%	105.0%	95.0%	97.2%	98.4%	74.2%
7%	93.0%	79.7%	70.5%	73.4%	74.3%	51.3%
10%	67.4%	51.6%	42.8%	46.6%	48.6%	35.1%
15%	35.4%	26.0%	21.1%	24.9%	26.6%	27.3%
20%	19.8%	12.6%	11.2%	14.1%	16.6%	25.5%
30%	5.3%	3.4%	4.2%	6.5%	9.0%	25.0%
50%	0.6%	1.2%	2.5%	4.2%	6.5%	25.0%

feasibility of this concept and that it can be utilized to transmit high-quality imagery based on or in conjunction with a shared model at a fraction of the transmission cost of transmitting a full image. The magnitude of change messages required has been shown to be highly related to the size of the initial model and threshold value selected. The minimal dithering performed on the 15% model size (as pixel-to-pixel upscaling was not possible) demonstrates the value of dithering (as this model consistently outperformed the larger 20% size). Incorporating dithering into the process for all model sizes will be the focus of future work.

11. CONCLUSION & FUTURE WORK

The work discussed herein has demonstrated the utility of the base component of the MBTR framework. Additionally, it has demonstrated a technique for image compression that focuses on maximizing the use of bandwidth by transmitting the most important features (in this case determined by the pixel difference value) first. This would result, in many cases, in features that were eliminated (due to being below the size required to equate to one or more pixels at the lower resolution) being added back in to the model/image with priority over more minor changes.

Future work will focus on the continued development of all aspects of the MBTR system. This will include additional work on the MBDT component – specifically, applying it to other types of data beyond imagery. It will also include work on developing the higher-tier members of the framework. Work is ongoing on utilizing the MBTR on actual small-satellite-grade hardware and applying the technology within a mission concept.

Figure 1: Asteroid Vesta [from 10] with 5% threshold and 10% model size

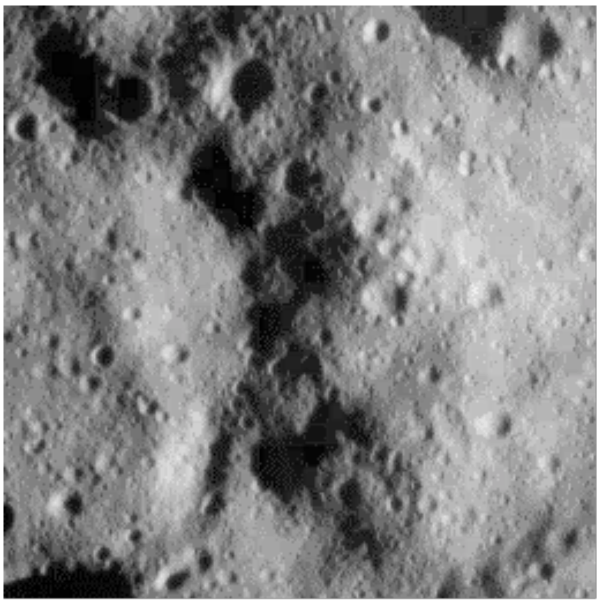

Figure 2: Asteroid Vesta [from 10] with 15% threshold and 10% model size

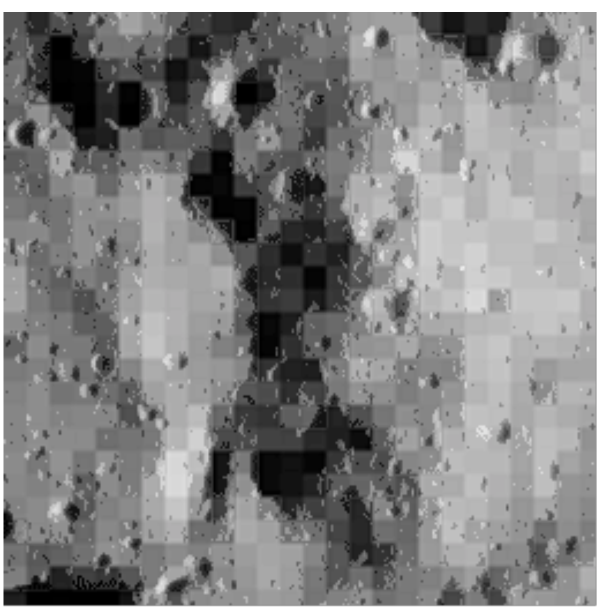

Figure 3: Asteroid Vesta [from 10] with 15% threshold and 25% model size

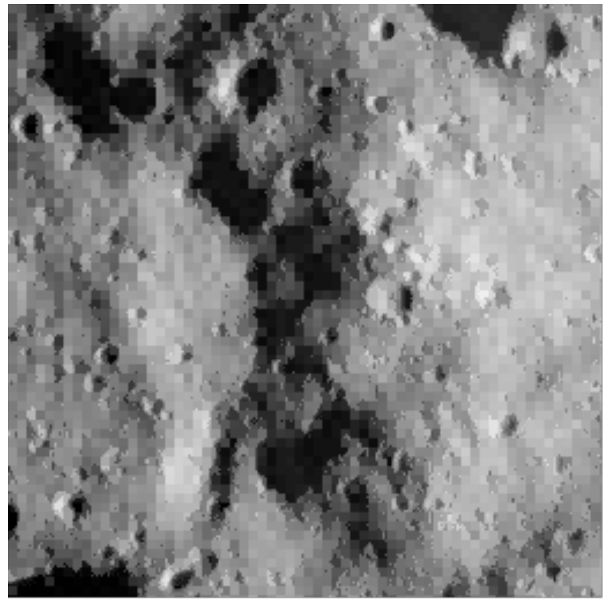

Figure 4: Asteroid Vesta [from 10] with 15% threshold and 50% model size

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the Office of the Provost. Trademarks mentioned are acknowledged to be the property of their owning entity.

Figure 5: Asteroid Vesta [from 10] with 50% threshold and 25% model size

Figure 6: Asteroid Vesta [from 10] with 50% threshold and 50% model size

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