Glaciers and Ice Sheets Mapping Orbiter

A concept submitted to

Decadal Study-Request for Information

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Abstract

We propose to develop and deploy a spaceborne radar system for measuring the surface and basal topography of terrestrial ice sheets and to determine the physical properties of the glacier bed. Our primary objective is to develop this new technology for obtaining spaceborne estimates of the mass of the polar ice sheets with an ultimate goal of providing essential information to modelers estimating the mass balance of the polar ice sheets and estimating the response of ice sheets to changing climate. Our technology employs VHF and P-band, multi-phase-center, interferometric radars for measuring the surface and bottom topographies of polar ice sheets. Our approach will enable us to eliminate signal contamination from surface clutter, measure the topography of the glacier bed, and paint a picture of variations in bed characteristics. The technology will also have applications for planetary exploration including studies of the Martian ice caps and the icy moons of the outer solar system. We have recently shown that is possible to image a small portion of the base of the polar ice sheets using a SAR approach. Through the concept proposed here, *we will, for the first time, be able to image the base and map the 3-dimenional basal topography beneath an ice sheet at up to 5 km depth.*

1 Glaciers and Ice Sheets Mapping Orbiter (GISMO) Description

1.1 Description of Proposed Measurement System Technology

We propose to develop a unique spaceborne interferometric sounder instrument for obtaining information that will contribute to the understanding of polar ice sheets and glaciers sufficiently to assess their contribution to global sea level rise. The sounder will operate at VHF and P-band (430 MHz) in interferometric mode at incidence angles near nadir. It will consist of two antennas for interferometric imaging ice sheets from a spacecraft in a polar orbit. The instrument will operate in a swath mode to achieve rapid coverage and to obtain imagery of basal properties. We will employ a novel filtering scheme applied to the interferograms to remove surface clutter and to obtain swath coverage of basal topography and basal reflectivity. We will design the instrument such that it can operate in nadir mode or swath mode at incidence angles near nadir and can collect interferometric data in single-pass mode with two antennas or repeat-pass mode. We will develop the system in terms of the following observational goals: *1) determine total global ice sheet volume by mapping surface and basal topography; 2) determine basal boundary conditions from radar reflectivity; and 3) understand the phenomenology of radar sounding of ice for applications to planetary studies.*

We propose to develop the instrument to meet the following measurement requirements:

1) Measure ice thickness and basal topography to an accuracy of 20 m or better;
2) Measure ice thickness every 1000 m (in some cases 500 m);
3) Measure ice thickness ranging from 100 m to 5 km;
4) Measure radar reflectivity from basal interfaces (relative 2 dB); and
5) Pole-to-pole observations

Our goal is to develop a spaceborne system for measuring the thickness and basal reflectivity of the Polar Ice Sheets and large ice fields located outside of the polar regions. The technology will also have applications for planetary exploration including studies of the Martian ice caps and the icy moons of the outer solar system.

1.2 Technical Approach

Current systems designed to map the basal topography and physical properties of the polar ice sheets are limited in three fundamental ways. First, aircraft supported missions are largely incapable of providing continental scale coverage in Antarctica because of the limited number of bases from which to operate. Second, the systems typically collect data along profiles so that 3-dimensional information must be gleaned from interpolation. Third, systems presently in use suffer signal degradation by surface clutter particularly in more dynamic areas of the ice sheet where the ice surface is rough. The later is one of the main reasons why airborne sounding radars are flown at low altitudes. Surface clutter is a much more severe problem for orbital sounding of polar ice sheets. We can obtain fine spatial resolution in two of the three dimensions. We can get fine range or depth resolution by operating the radar at a suitable center frequency with sufficient bandwidth. Using the satellite motion we can synthesize a long aperture to obtain fine resolution in the along-track direction. However, constraints on the antenna size and the need to operate at long radar wavelengths to sound thick ice result in poor resolution in the cross-track direction. This poor resolution poses a major challenge for obtaining adequate surface clutter rejection for spaceborne sounding of polar ice sheets. Sub-surface sounding of Mars and ice moons of Jupiter also poses a similar challenge.

1.2.1 Spaceborne Mission Instrument Description:

We propose a novel interferometric system capable of overcoming the surface clutter problems for a short duration mapping of the polar regions, leading to significant gains in science capability and cost reductions over current approaches. Our proposed system consists of a synthetic aperture radar interferometer (IFSAR) operating at P-band and using a 45 m interferometric baseline. A VHF system is also under consideration. We restrict data collection to near nadir incidence angles leading to a 50-km swath that starts at a cross-track distance of 10 km from the nadir track. Table 1 presents detailed system parameters and Figure 1 presents the expected signal-to-noise and signal-to-clutter performance for 2-km thick ice. Satisfactory signal–to-noise ratios are achieved for ice depths up to 4 km. Clutter contributions are the primary noise sources to the signal over the swath. The following section discusses how we propose to remove clutter and make decisions about final system parameters. Here, we briefly discuss the system design.

Table 1: Spaceborne System Parameters	**Value**
Number of channels	4 (polarimetric)
Center frequency	430 MHz
Bandwidth	6 MHz
Pulse Length	20 μsec
Peak Transmit Power	5 kW
Orbit Repeat	2 weeks
Orbit Type	Polar
Platform height	600 km
1-Look Azimuth Resolution	7 m
Pulse Repetition Frequency	10 kHz
Antenna diameter	12.5 m
Antenna Type	Mesh Reflector
Boresight Angle	1.5 deg
Interferometric Baseline	45 m
Resolution after taking looks	1 km
Minimum number of looks	500

As soon as an off-nadir swath is required, brightness returns from a surface are insufficient to estimate height and an interferometric radar is required. The height accuracy which can be achieved with an interferometer depends on the signal-to-noise (SNR) and signal-to-clutter (SCR) ratios, the number of radar looks, and the interferometric baseline [Rodriguez and Martin, 1992] [Rosen et al., 2002]. Modifying the equations in those references to include ray bending and the presence of a second surface which generates clutter contamination, we can derive the expected retrieved height accuracy as a function of SNR and SCR. Figure 2 shows the expected performance of the system given the parameters in Table 1. It also shows that, due to the large number of looks and the 1 km spatial resolution, an SNR between –5dB and 0 dB is sufficient for achieving the desired height accuracy out to 60 km cross track distance. It also shows that the clutter reduction need not be perfect: achieving rejection ratios so that the final SCR is in the range between –10 dB and 0 dB is sufficient to meet the science requirements.

We have selected the system to operate at 430 MHz for several reasons: 1) antenna size reduction; 2) baseline reduction so that it is achievable in a single spacecraft; and, 3) field experiments have shown that the attenuation due to ice propagation is relatively constant over the frequency range from 100 to 500 MHz [Paden et al., 2004]. The main disadvantage of P-band is higher surface clutter. We propose to show that the clutter problem can be solved using a P-band radar, or to modify the proposed spaceborne design (Table 1).

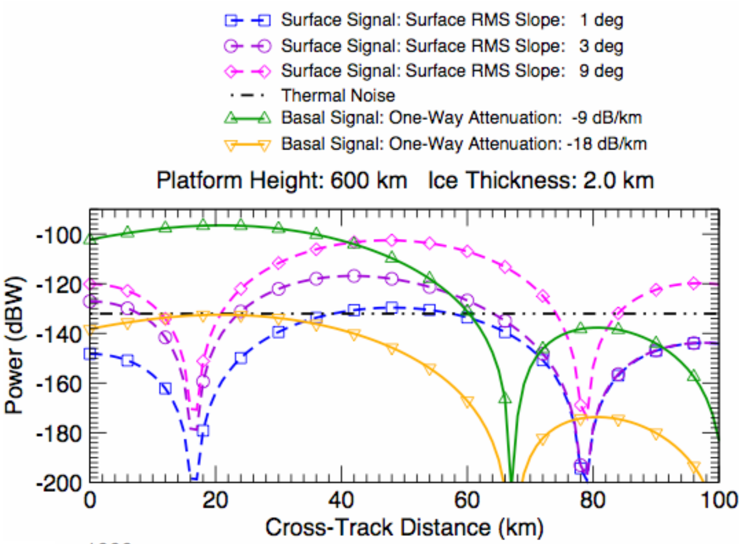


Figure 1*:* *Expected signal to noise and signal to clutter ratios for an ice thickness of 2 km and for various surface clutter (which depends on the rms slope of the ice sheet surface) scenarios. As can be seen from this figure, the instrument performance is limited by the clutter.*

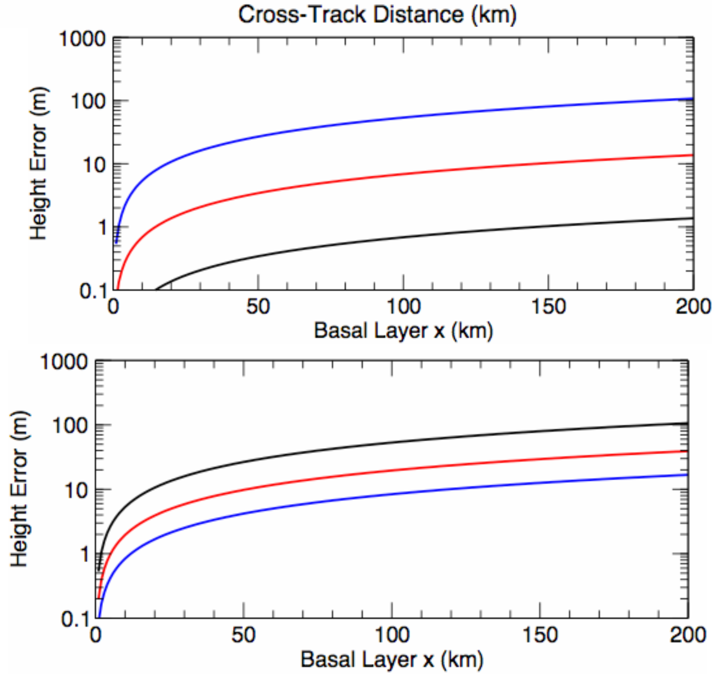


Figure 2*:* *(Top Figure)* *Height error across the swath as a function of signal-to-clutter ratio SCR (SCR) for values of 0 dB (black), -10 dB (red), and –20 dB (red).* ***(Bottom Figure)*** *Height error cross the swath as a function of signal-to-noise ratio (SNR) values of SNR of 0 dB (blue), -5 dB (red) and –10 dB (black)*

We have selected a polarimetric system to allow for corrections due to ionospheric distortions and Faraday rotation. Freeman [2004] and Freeman and Saatchi [2004] have shown that using polarimetric returns, one can achieve an azimuth resolution commensurate with our 1 km spatial resolution requirement and not lose significant signal power due to Faraday rotation (Liu and others, 2003). As part of the proposed work, we will be building upon that work to adapt it to obtain calibration algorithms for our design.

1.2.2 Interferogram Filtering for Clutter Cancellation

The idea behind interferometric filtering for clutter reduction is based on the fact that scattering from ice sheets consists of three components: a) ice-air interface and near surface density variations; b) ice-bed interface; and c) intermediate layers, due mainly to changes in conductivity. The intermediate layers are weakly scattering even in the specular direction (reflection coefficients of –60 to –80dB) and can be neglected at off-nadir incidence. Thus off-nadir scattering can be treated as resulting from two interfaces. The top interface is relatively smooth in the interior, whereas the bottom interface can be varying degrees of roughness. Because the speckle from the two interfaces is not correlated, the average radar interferogram, a complex product between the two interferometric channels, can be modeled as the sum of the interferogram from the basal and surface layers. In the near-nadir direction, the basal fringes (which are due to scattering near nadir) will vary much faster with range (or cross-track distance) than fringes from the clutter (which is generated at larger angles). Basal layer slopes, and, to a lesser degree, ice sheet slopes, will modulate the fringe rate, but in the near nadir direction the main contribution to the fringe rate will be the flat surface term, and surface slopes only play a secondary role. Figure 3 shows the result of Fourier transforming the sum interferogram for our system.

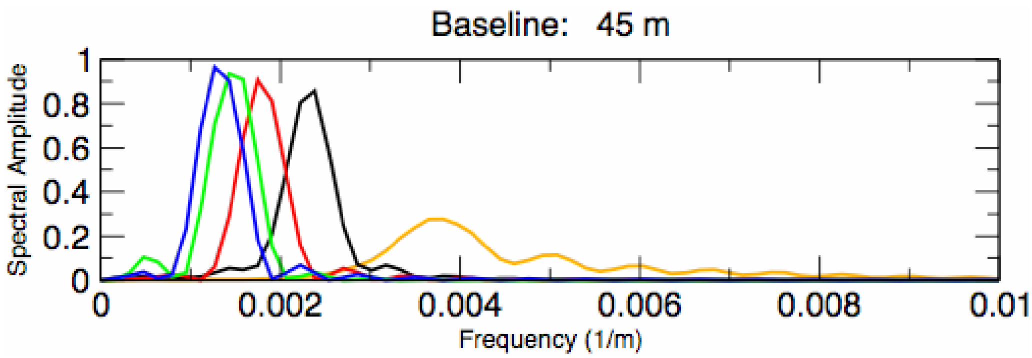


Figure 3: *Spectrum of the interferogram for the basal return (orange) and for the surface return for ice depths of 1 km (black), 2 km (red), 3 km (green), and 4 km (blue). The signal to clutter ratio has been assumed to be 0 dB. The spectral amplitude is in relative units. Only positive spatial frequencies are shown.*

We assumed that the SCR is 0 dB and ice thickness varies between 1 km and 4 km. The results clearly show that the surface and basal mean interferograms are well separated in spatial frequency. Thus we can separate the two signals with an appropriate filter. A major goal of our proposal is to demonstrate this through theoretical simulations and airborne experiments. The results presented are for flat ice and basal layers, but it can be shown that at near-nadir-incidence, fringe rate due to changes in surface slope are much smaller than changes due to the incidence angle. Since the interferogram is a complex signal, positive and negative frequencies can be separated. Because interferometric phase has opposite sign for objects to the left or right of the nadir track, the complex spatial frequencies will also have opposite signs. Thus we can differentiate signals from right and left by selecting the proper side of the Fourier spectrum.

There are two complications with the spectral separation we show in Figure 3. First speckle noise for a single-look interferogram will generate signals at all spatial frequencies and mix signal and clutter. This effect can be mitigated using the fact that speckle noise can be reduced by multi-looking interferograms. In our design, we propose to take a substantial number (500 minimum) of looks so that the broadband speckle noise is substantially reduced. Although averaging results in a decrease of spatial resolution, it is still sufficient to meet the science requirements. Another potential problem arises due to the fact that the surface and basal reflectivities will have spatial variations, which will lead to spectral broadening. Surface scattering from the interior ice sheet is relatively homogeneous, so we expect that the spectral broadening of the surface return will be small. The basal return can have greater variability, but most of the broadening is expected at high frequencies so that we expect that the spectral separation will be maintained. Nevertheless, the exact magnitude of this corruption must be obtained by experimental measurements as is also the case for the actual magnitude of the SCR at P-band. It is precisely these measurements which we propose to make to demonstrate the validity of this approach.

At first glance, it might appear that we are extracting more information from the interferogram than is really there: after all, radar interferograms are traditionally used to derive heights only. However, we are using additional information not traditionally used in interferometry: namely, the spatial characteristics of the interferometric fringes. To make this useful, we have to assume that the scattering is effectively from only two surfaces. We also degrade the final spatial resolution relative to the instrument intrinsic spatial resolution. These sacrifices are not acceptable for most interferometric applications, but they are acceptable for our application over polar ice where the volume is only a source of weak scattering.

2 GISMO Contribution to Earth Science

2.1 Climate Variability and Change

Glaciers and ice sheets modulate global sea level by storing water deposited as snow on the surface and discharging water back into the ocean through melting and via icebergs. Only recently have we recognized, primarily from satellite observations, that the size of this frozen reservoir can change as demonstrated by the rapid thinning of Jacobshavn Glacier in Greenland (Thomas, et. al., 2003), the Pine Island and Thwaites Glaciers in Antarctica (Rignot, 2001) and the demise of the Larsen Ice Shelf followed by thinning of interior Antarctic Peninsula Glaciers (Scambos and Shuman, 2004). Yet none of these events are captured by current glaciological models suggesting that there are critical gaps in observations and theory about the dynamics of large ice sheets.

Missing from the constellation of satellites currently observing the polar regions, is a sensor capable of probing the volume of the ice sheet and measuring the topography and properties of the glacier bed. While much work has been done to measure ice thickness from aircraft, gaps in coverage remain especially over part of Antarctica (ISMASS Comm., 2004). Very little information is available about variations in properties of the subglacial bed where we believe critical changes in the control on ice sheet flow takes place. We propose to develop a new sensor to probe, systematically and comprehensively, the base of the polar ice sheets. We ultimately seek to perform pole-to-pole measurements of glacier and ice sheet thickness, basal topography, and physical properties of the glacier bed that will help to answer two fundamental questions: *What is the impact of changing ice sheets on global sea level rise?; Can we predict changes in ice sheet volume and hence changes in global sea level as global climate changes?*

Two concepts demonstrate the fundamental role of ice thickness and basal physical properties in understanding and predicting ice sheet behavior. The physical state of glaciers and ice sheets can be characterized in terms of their mass balance and dynamics. The mass balance is described by the mass continuity equation given as

$$\frac{dh}{dt} = -\nabla \bullet H\vec{U} + \dot{a}$$

where h is the surface elevation, H is the ice thickness, U is the velocity and a is the accumulation rate. The left hand side represents the change in ice elevation with time (assuming that the bed is fixed). It is best measured by altimeters that have now been operated over decadal intervals with great success. But they are susceptible to errors due to factors such as changes in the near surface density unrelated to changes in the mass balance. The right hand side represents the state of balance between the outward flux of ice and the ice accumulated on the surface (or base). Because of measurement techniques, it can represent a slightly different estimate than that captured by altimeters. Point values of U as well as spatial gradients in U and H do not react instantaneously to changes in temperature or accumulation rate. So mass balance estimated using surface velocities, accumulation rate and available estimates of ice thickness yield a mass balance estimate that reflects an averaging over time.

Insight into the forces controlling ice sheet shape and motion comes from dynamical equations usually written in terms of equalities between depth averaged stresses and gradients in depth integrated stress. For example, it is easily shown that for a simple model consisting of a glacier driven under its own weight and restrained by forces at the sides and the bottom that

$$\tau_d = \tau_b + \frac{H}{w}\tau_s$$

where the driving stress (τ_d) is proportional to the product of ice thickness and surface slope, τ_s is side drag, w is the width of the glacier, and τ_b is the basal drag (Van der Veen, C.J. 1999). Information on τ_s can be computed from InSAR surface velocities and ice rheological properties. The driving stress is computed from altimeter derived surface slopes and available knowledge on ice thickness. The basal drag term is usually deduced.

By combining equations describing the balance of forces in a glacier with knowledge about ice rheology and with the continuity equation, it becomes possible to build models that predict how changes in climate forcings or internal forcings (such as changes in the amount of water at the base of a glacier) will change the mass balance. Of the variables needed to solve these equations, ice thickness and information the properties of the glacier bed (τ_b) are most poorly determined. Improving ice thickness knowledge will yield two important results. First, the right and left hand sides of the continuity equation can be solved separately using, on one hand, the results from spaceborne altimeters, and on the other hand, the results from spaceborne InSAR-derived velocity data, spaceborne passive microwave observations of accumulation rate along with the improved knowledge of ice thickness. The two estimates will not necessarily equate for the reasons given above and indeed the difference might tell something about the differences between the short term and average state of ice sheet mass balance. Second, improved ice thickness and basal characteristics data will refine our understanding of the forces acting on glaciers. This information will provide modelers with a considerably enhanced data set for estimating future changes in global glacier cover and its contribution to sea level rise.

2.2 Relationship to other National and International Programs

Ice thickness, basal topography and basal physical properties observations will provide improved estimates for the potential contributions of glaciers and ice sheets to sea level rise. Our proposal is targeted ***toward quantifying the mass of sea or land ice and how it is changing***. Combined with data from other sensors, these observations will provide modelers with fundamental information for measuring the mass balance of the ice sheets and for developing models, which explore how the ice sheets will change with changing climate and the consequent impacts on global sea level. Our proposed measurement and instrument concept complement international efforts including the Scientific Committee on Antarctic Research ISMASS group and themes which are emerging from the cryospheric working group that is part of the International Global Observing System committee structure.

2.3 Applications to the Exploration of the Solar System

We also note that this technology has applications to the scientific exploration of extraterrestrial icy worlds. Surface clutter is a measurement obstacle common to studies of the Martian ice caps as well as to planned studies of the icy moons of the outer solar system. Our technical concept will find important applications for studying the dynamics of the Martian ice caps for and probing the volume of the ice shell suspected of enclosing a liquid ocean on Europa.

2.4 Technology Assessment

We propose an instrument which would be able generate swath maps of ice basal topography, a measurement not previously possible from space. Conventional sounders are profiling instruments: their data consists of backscatter measurements as a function of return time, which can be interpreted as depth below the ice surface. Their spatial resolutions are typically limited by their bandwidth (the pulse-limited footprint) and for spaceborne instruments are typically on the order of several kilometers.

A further and greater limitation of spaceborne sounders is caused by the signal contamination due to surface clutter. The clutter suppression concept is very difficult to implement from space: for example, the ambiguous return for an ice depth of 1 km observed by a sounder from a height of 600 km would require that the antenna beam be much smaller than 3 degrees. Assuming that one must be at least 2 to 3 beamwidths away from the main lobe to reach the appropriate level of clutter cancellation, this would require and antenna width of 30 m to 40 m at UHF frequencies and approximately 3 times larger at VHF. These antenna sizes, although conceptually realizable, are not yet mature and will likely lead to large mission costs due to launch vehicle and bus requirements. The technology we propose has significant advantages over other concepts for spaceborne sounders:

Swath Mapping: The system we propose will have a swath of 50 km. This will enable mapping of all latitudes above 60 degrees 200 passes (assuming ascending and descending data collection) which given a typical number of 14 passes per day would enable the collection of the entire polar regions above 60 degrees in 14 days. This implies that with a mission lifetime of 3 months, one would be able to map Antarctica and Greenland about 6 times, to reduce random and systematic height errors. In comparison, assuming a profiling instrument of the desired resolution will require a total mission lifetime of about 4 years.

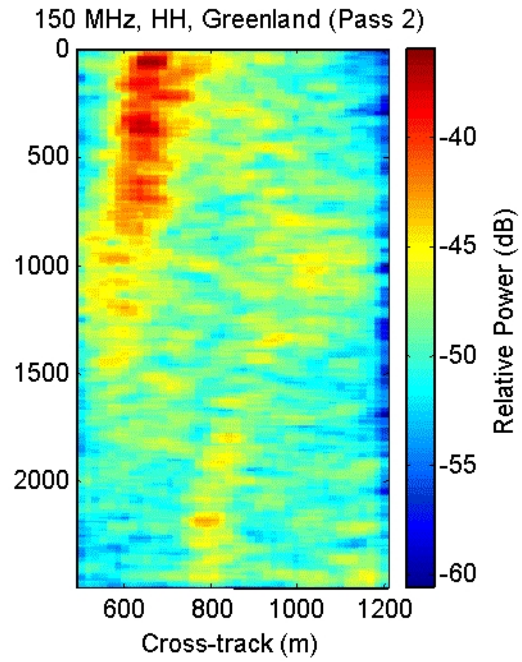
Smaller Antennas: The system concept we are advocating will require a 12.5 m diameter reflector antenna at P-band. These antennas have been successfully flown in space for telecommunication applications.

Direct Height Measurements: Sounder returns are maps of radar reflectivity as a function of depth which must be interpreted through waveform retracking to convert to basal depth. The interferometric measurement is a direct measurement of height. The estimated accuracy for single pass measurements is predicted to be better than 10 m, so that over a 3 month mission one could expect height accuracies on the order of 4 m or better (assuming uncorrelated errors

Separation of Basal and Clutter Signals: The interferometric filtering technique presented above will allow for the separation of ice surface and basal signals. This is not possible with conventional sounding.

Ice Imaging Demonstration: Within the past year, we succeeded in demonstrating that the base of the Greenland Ice Sheet could be successfully imaged with a 150 MHz radar operating on the ice sheet surface. The resulting SAR image is shown in figure 4. While we are just beginning our interpretation of the images collected near the central ice divide of the ice sheet, the example demonstrates that backscatter variations from the ice sheet/bedrock interface are measurable.

Figure 4. 150 MHz SAR Image acquired at Summit Camp, Greenland (Ice thickness: 3000 m)



3 Proposed Costs

We estimate that this will be a mid sized mission. Primary costs will be associated with instrument and satellite development and satellite launch. Mission operations costs will be minimized because the mission can be completed in about 1-year of operations.

Launch Vehicle:	$40M
Instrument:	$70M
Spacecraft	$50M
Project Management	$73M
Flight Systems	$145M
Phase E	$30 M
Reserves	$65 M
Total	$473 M

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